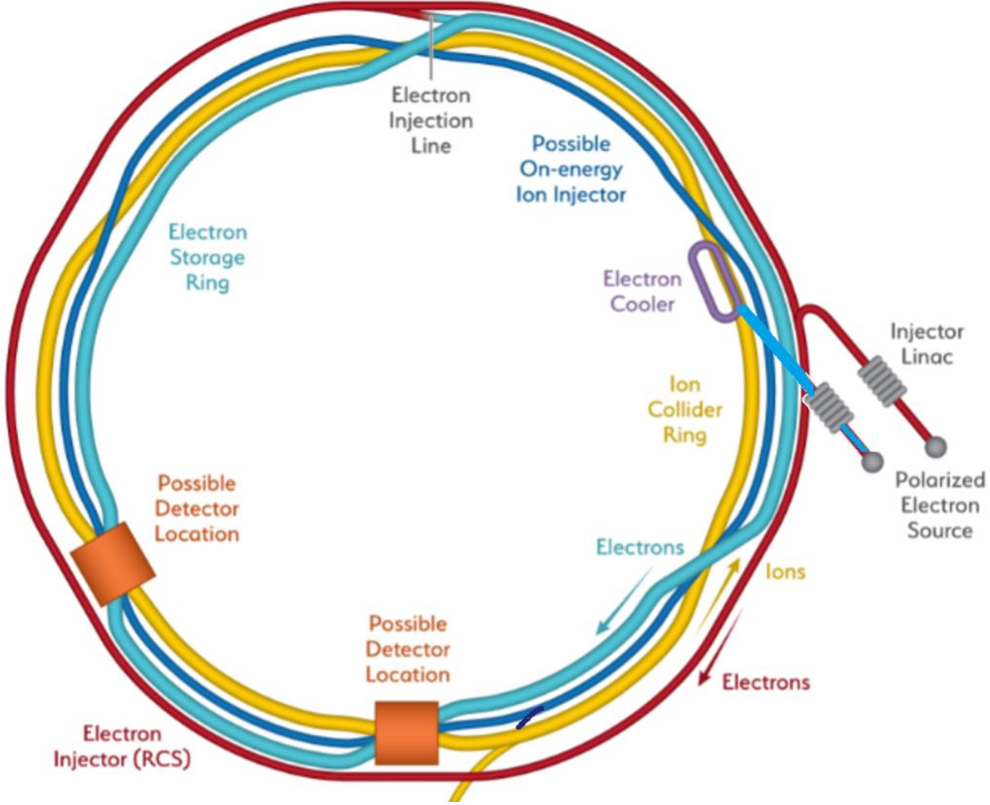
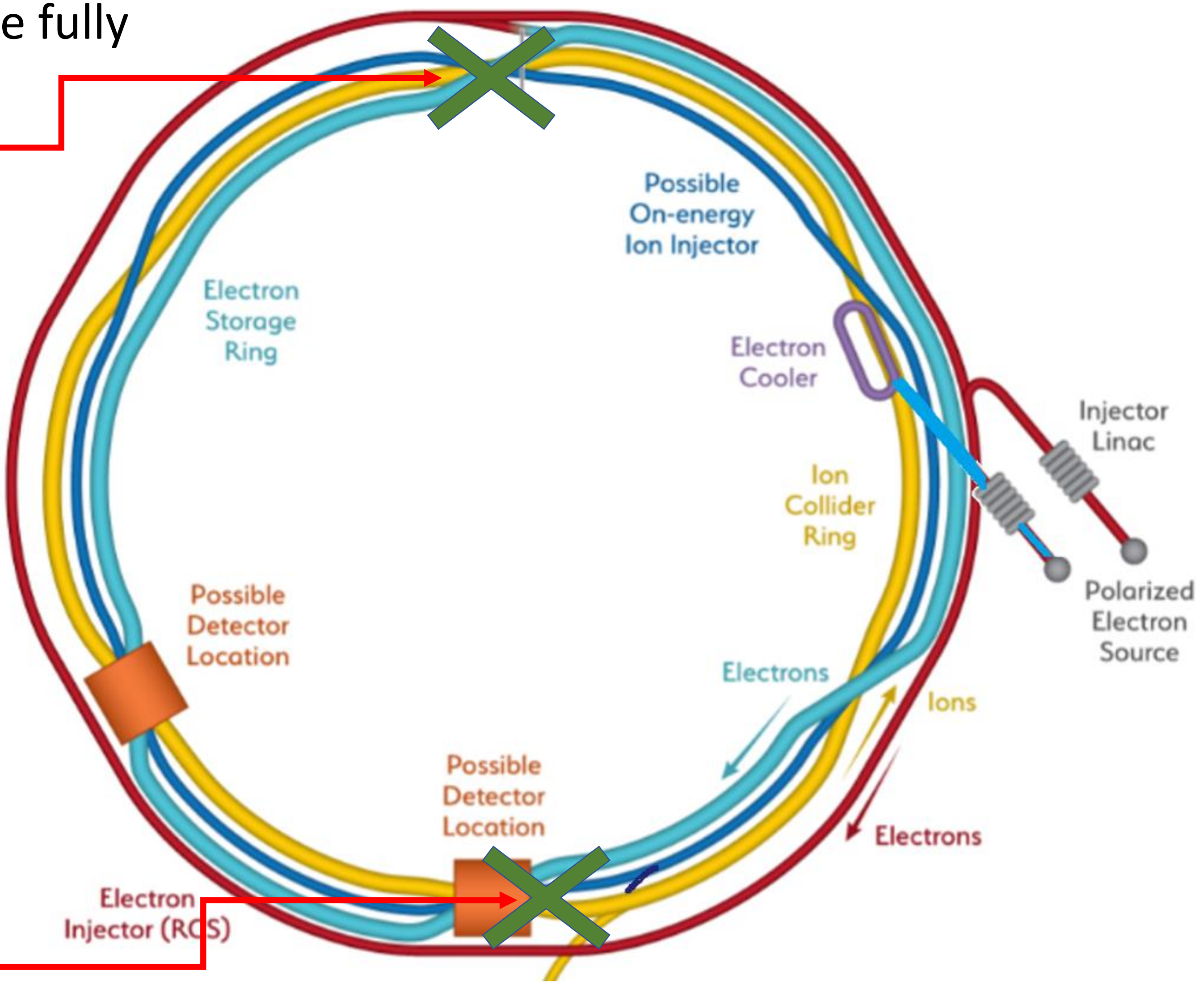
EIC Compton laser

Ciprian Gal, Abhay Deshpande, Dave Gaskell,
Kent Paschke, Shukui Zhang



e-Polarimetry at the EIC

At the IP12 location beam will be fully transverse



Close to the experimental IR it will be a mix (mostly longitudinal)

e-Polarimetry requirements for the EIC

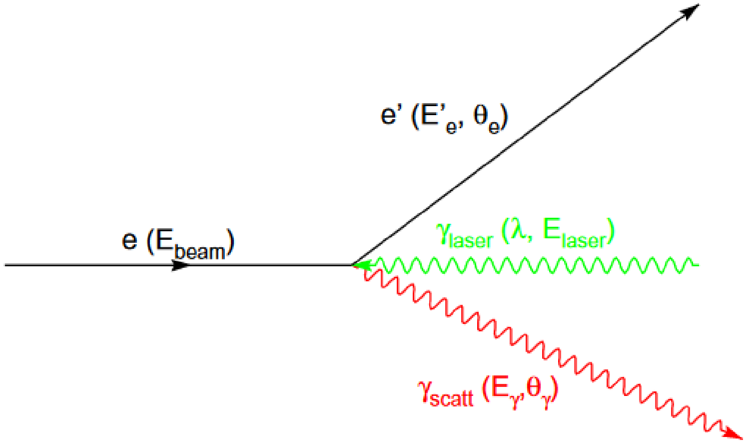
Fast

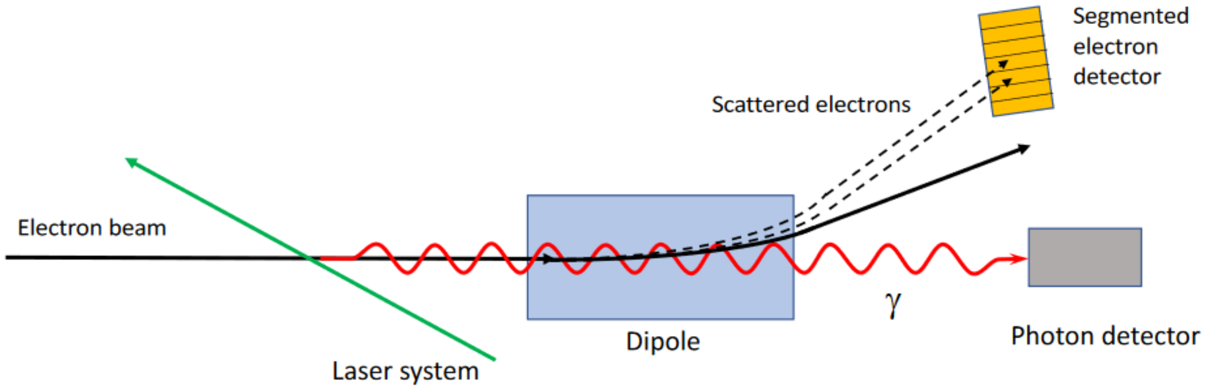
- At 18 GeV bunches will be replaced every 2 min
  - A full polarimetry measurement needs to happen in a shorter time span
- The amount of electrons per bunch is fairly small ~24 nC
  - will need bright laser beam to obtain needed luminosity
- A fast polarimeter will allow for faster machine setup

Precise

- Distance between buckets is ~10ns (@5,10 GeV)
  - bunch by bunch measurement cannot be done with a CW laser without very fast detectors
- For systematic studies we would like to have the ability to either measure a single bunch (~78kHz) or have interactions with all 1160 (260) bunches at 10 and 5 GeV (18GeV)
- Backgrounds needs to be under control
- Laser polarization needs to be known to a high degree

Compton scattering basics





- Polarized photon-electron scattering
- Potential to measure redundantly with scattered photon and electron
- Fully QED calculable analyzing power
- Interactions happen with a small fraction of the beam particles leaving it undisturbed
  - Monitoring can be performed in real time during actual data taking

Compton polarimeters through history

Polarimeter	Energy	Total Sys. Uncertainty	Type of laser	Measurement type
CERN LEP (T)	46 GeV	5%	~10s Hz pulsed Nd:YAG (532nm): 50 -100 W	Multi-photon
HERA (T)	27 GeV	1.9%	CW 10W (514.5nm) Argon	Single-photon
HERA (L)	27 GeV	1.6%	100Hz pulsed 10W Nd:YAG (532nm)	Single/Multi-photon
HERA (L)	27 GeV	1%	CW cavity 3 kW,	Single-photon
SLD at SLAC (L)	45.6 GeV	0.5%	17 Hz pulsed ?? W Nd:YAG (532nm)	Multi-photon
JLab Hall A (L)	1-6 GeV	1-3%	CW cavity 3.7 kW Nd:YAG (532nm)	Single/Multi-photon
JLab Hall C (L)	1.1 GeV	0.6%	CW cavity 1.7 kW Nd:YAG (532nm)	Single/Multi-photon

- Beyond LEP there were quite a few transverse polarimeters around the world that were used for beam diagnostics (an absolute polarization was not in the plan)
- Pulsed lasers generally tend to give more interactions per crossing so a multi-photon (or integrating) method was employed

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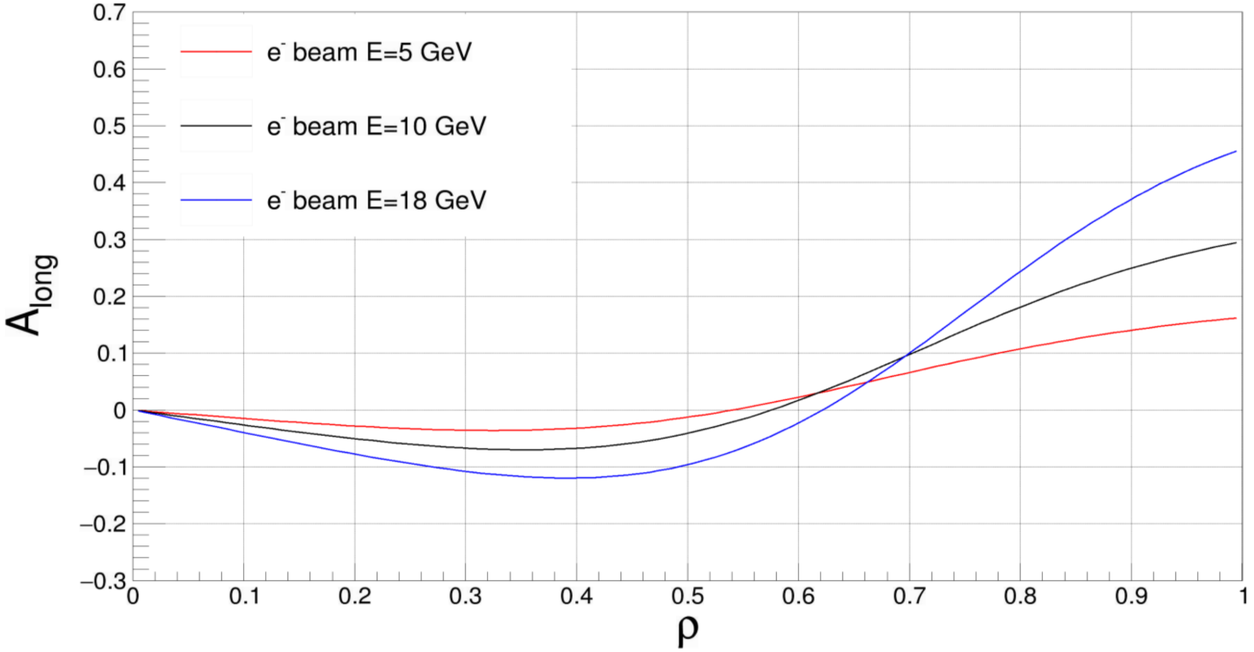
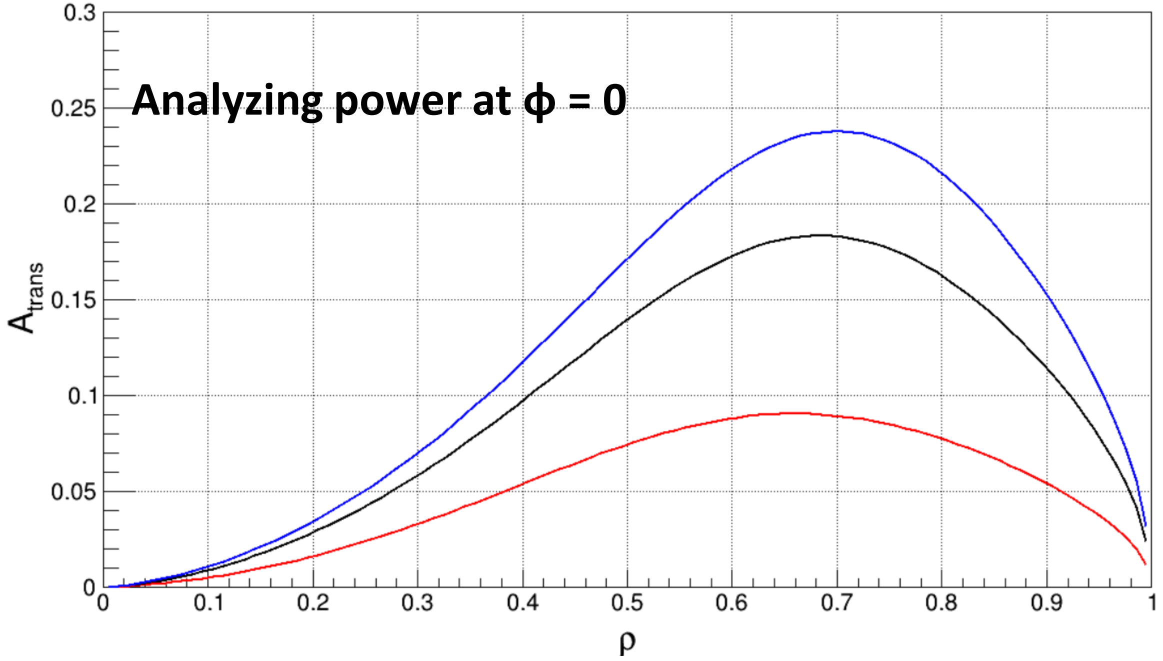
$$A_{\text{long}} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1 - \rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2}\right]$$

$$A_{\text{tran}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a)\frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))}\right]$$





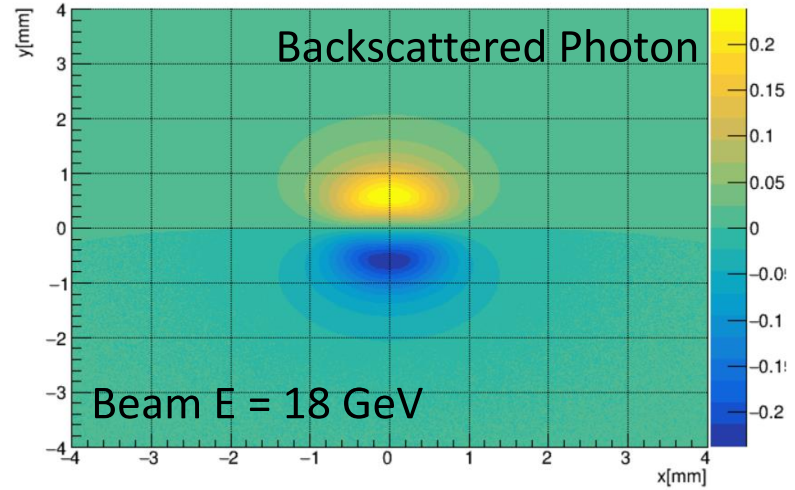
- Calculations based on 532nm laser system
- For both the longitudinal and transverse polarimetry measurements at the energies of interested for the EIC the analyzing powers are significant

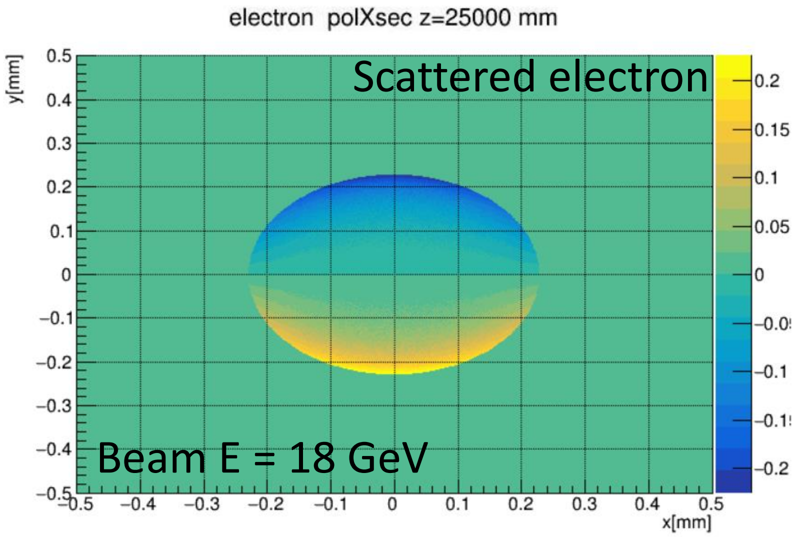
$$E_\gamma \approx E_{\text{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2}, \quad a = \frac{1}{1 + 4\gamma E_{\text{laser}}/m_e}.$$

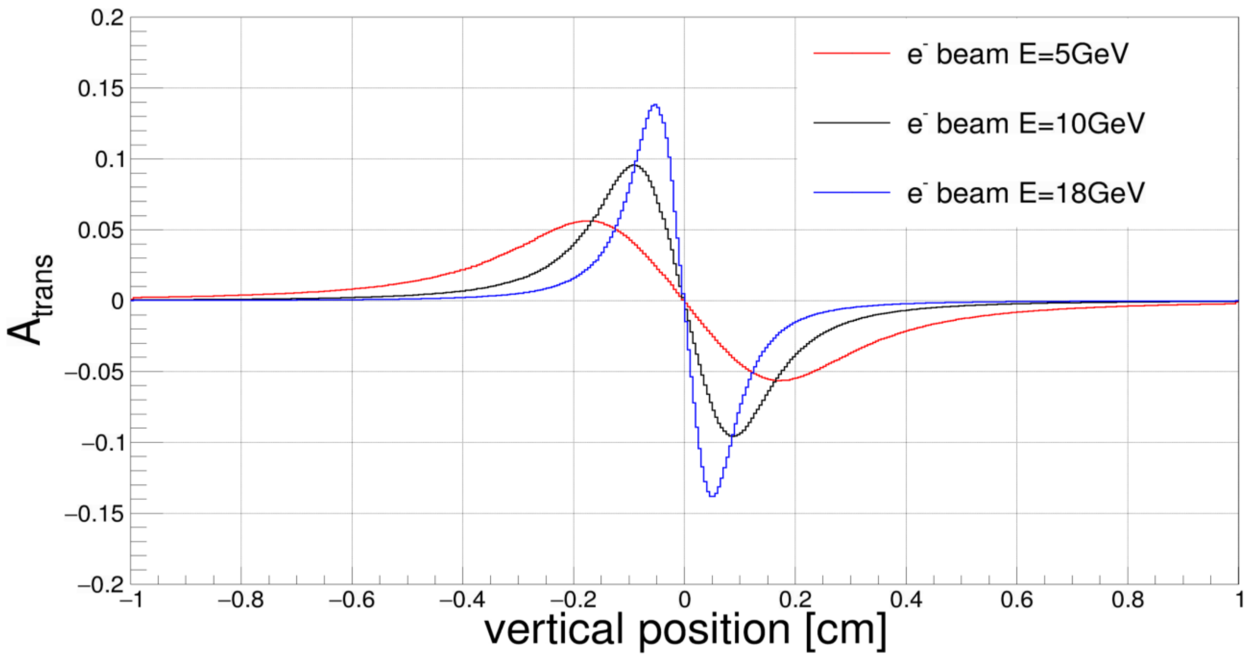
$$E_\gamma^{\max} = 4aE_{\text{laser}}\gamma^2, \qquad \rho = E_\gamma / E_\gamma^{\max}$$

Transverse polarization

$$A_{\text{tran}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a)\frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))}\right]$$







- Asymmetry is usually measured with respect to the vertical axis
  - The scattered electron reaches the largest analyzing power at large scattering angles
- The higher the energy the tighter the collimation of the scattered photons will be
  - This leads to significant constraints on detector segmentation

Luminosity calculations for individual bunches

$$N_{Compton} = \frac{\mathcal{L} \cdot \sigma_{unpol}}{f_{beam}}$$

$$t_{meth} = \left(\mathcal{L}\, \sigma_{\rm Compton}\, {\rm P_e^2 P_\gamma^2} \left(\frac{\Delta {\rm P_e}}{\rm P_e}\right)^2 {\rm A^2_{meth}} \right)^{-1}$$

G. Bardin, et al., Conceptual design report of a compton polarimeter in cebaf hall a, JLab Internal note.

- Assuming one scattered particle per bunch would allow us to calculate the luminosity needed and a time estimate for how long it would take to reach a 1% statistical precision

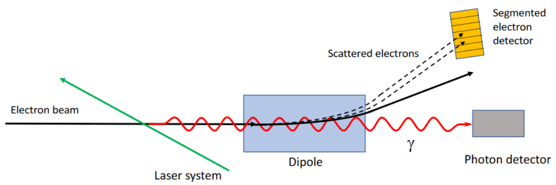
Beam energy [GeV]	Unpol Xsec[barn]	AN	t[s]	t[min]	L [1/(barn*s)]
5	0.569	0.029	210	3.5	1.37E+05
10	0.503	0.050	72	1.2	1.55E+05
18	0.432	0.075	31	0.5	1.81E+05

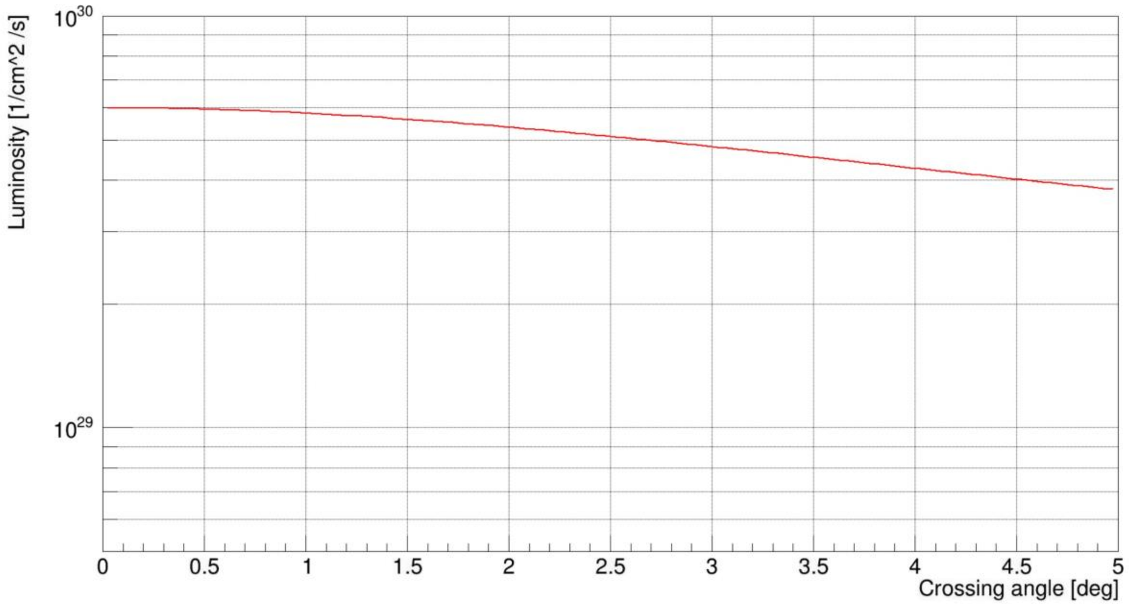
- For all configurations envisioned for the EIC (5-18 GeV) the luminosity requirements are on the level of few 1/(barn*s)
- The times needed to the needed statistics for the signal are on the level 30s at 18 GeV
  - Lower energies are less of a concern due to the longer lived stores
  - This would allow for simultaneous measurement of all bunches (given a fast detector)

Luminosity calculations for individual bunches

$$\mathscr{L} = f_0 N_1 N_2 \frac{\cos(\theta/2)}{2\pi} \frac{1}{\sqrt{(\sigma_{x,1}^2 + \sigma_{x,2}^2)}} \times \frac{1}{\sqrt{(\sigma_{y,1}^2 + \sigma_{y,2}^2)\cos^2(\theta/2) + (\sigma_{z,1}^2 + \sigma_{z,2}^2)\sin^2(\theta/2)}} \quad (1)$$

S. Verdu-Andres (CAD): https://www.bnl.gov/isd/documents/95396.pdf





- The dependence of the luminosity of crossing angle needs to take into account the transverse profile of the beam and the length of the pulse
- The estimation on the left is made for a single pulse
- For a 10W 100MHz pulsed laser with a 12ps pulse can provide about $6*10^5$ 1/(barn*s) of luminosity
    - Comparing this to the single photon measurement luminosities shows that such a laser will be sufficient

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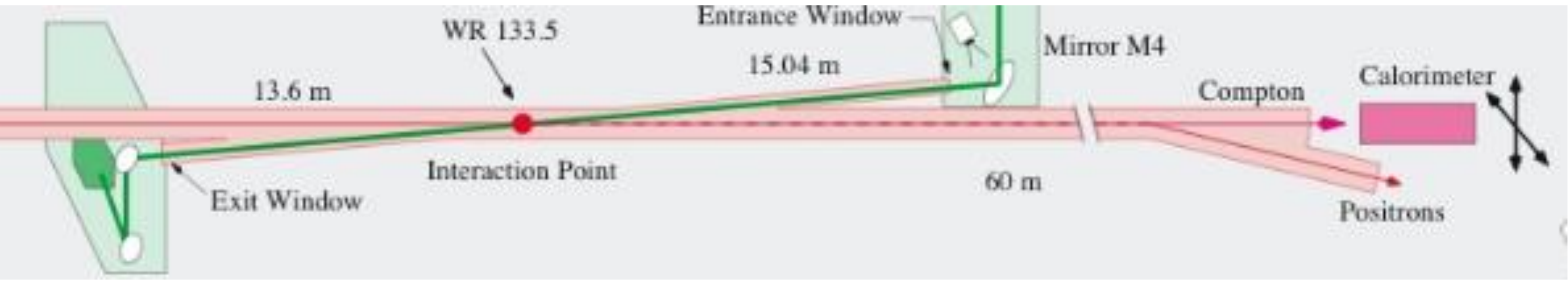
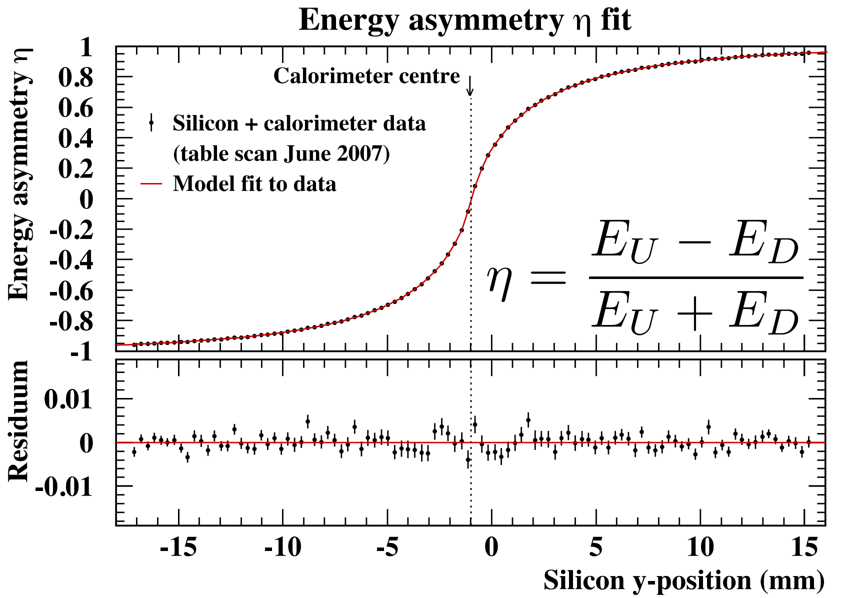
- Laser polarization needs to be known to a high degree

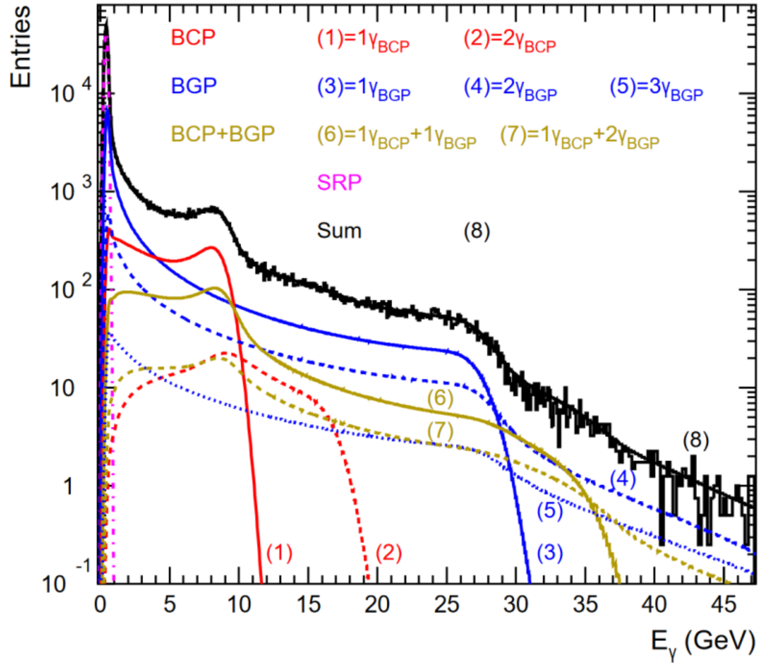
HERA Transverse Polarimeter



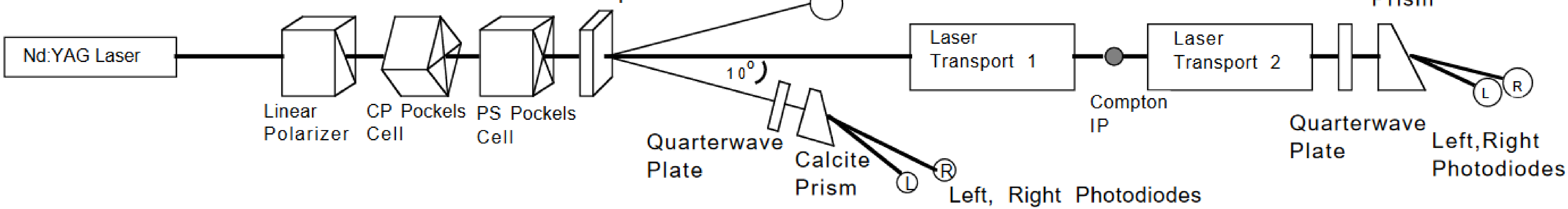


B. Sobloher et al, DESY-11-259 , arXiv:1201.2894

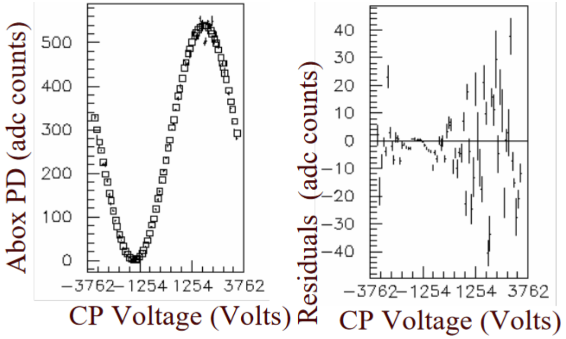
- Measurement extracted from an up-down energy asymmetry
- Chopper used for making background measurement
- Background measurements (and simulation cross checks) are very important to reach high precision
  - Beyond Compton scattering we need to measure beam only and laser "only" backgrounds (flexibility for the laser is crucial)
- Leading systematic was related to the detector
  - Systematics for laser were lower



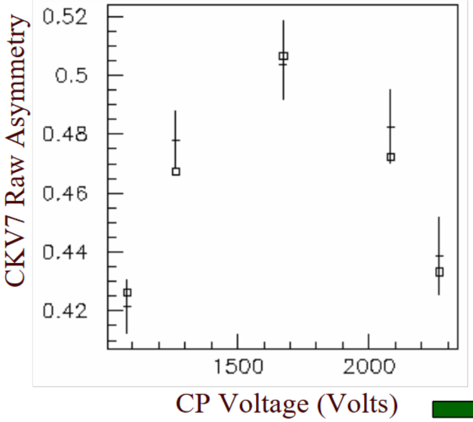
Compton laser setup



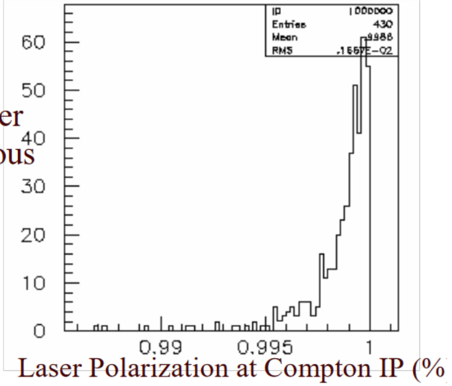
- The Compton laser systems are fairly standard
  - The SLD laser monitoring setup already had most of the tools we would need
- Scans performed with the PC during the experiment and data taking allowed for significantly reduced systematics related to the polarization state of the laser



LPSCANS
- done once per hour; readout photodiodes only
- ability to extinguish laser light after Helicity Filter determines polarization purity



ESCANS
- monitor phase shifts in laser Polarization with continuous Pockels cell scans
- only 1/3 of data is at nominal voltages

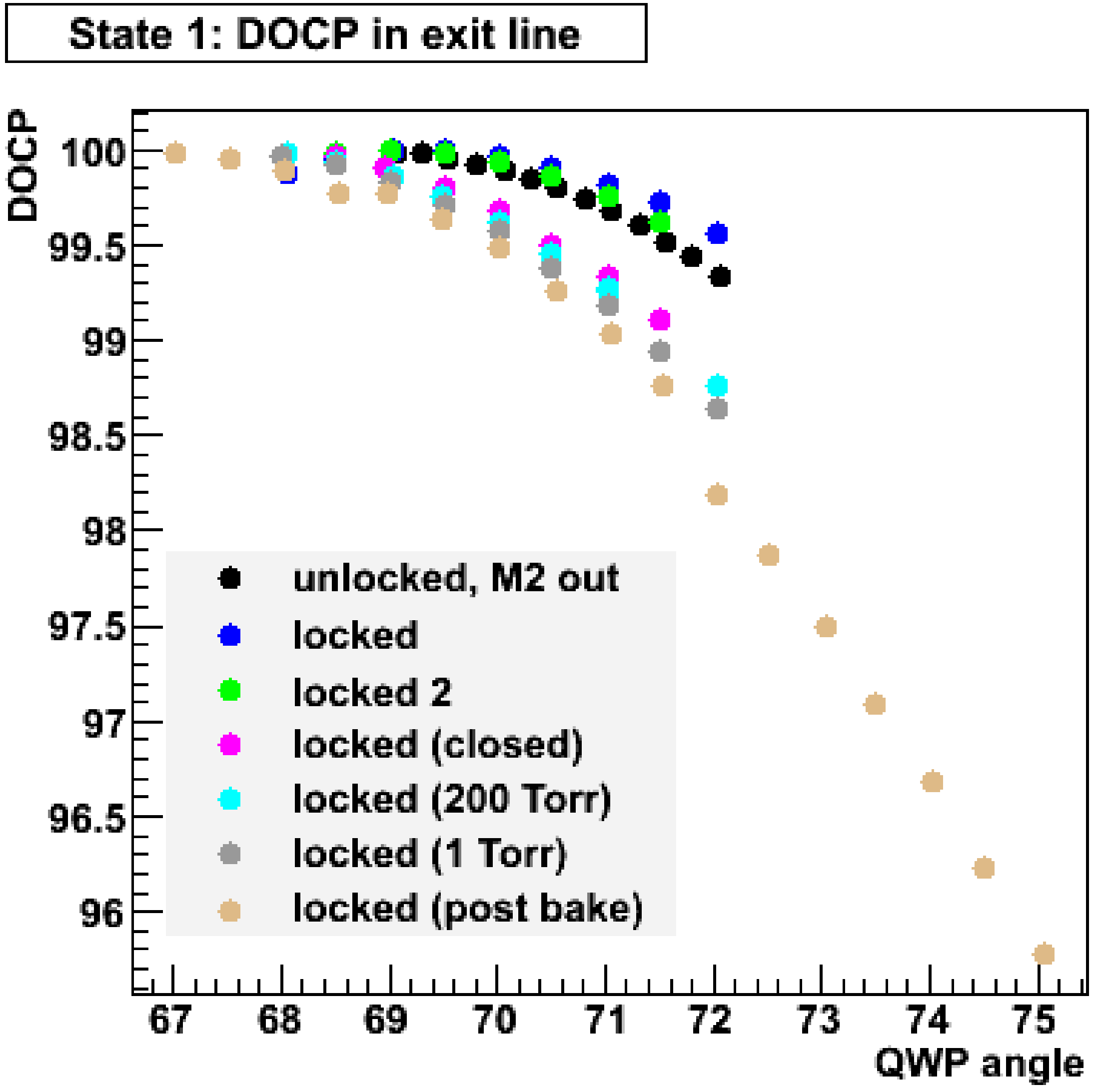


→ **0.1% systematic error**

M. Woods, SLAC

DOCP through windows

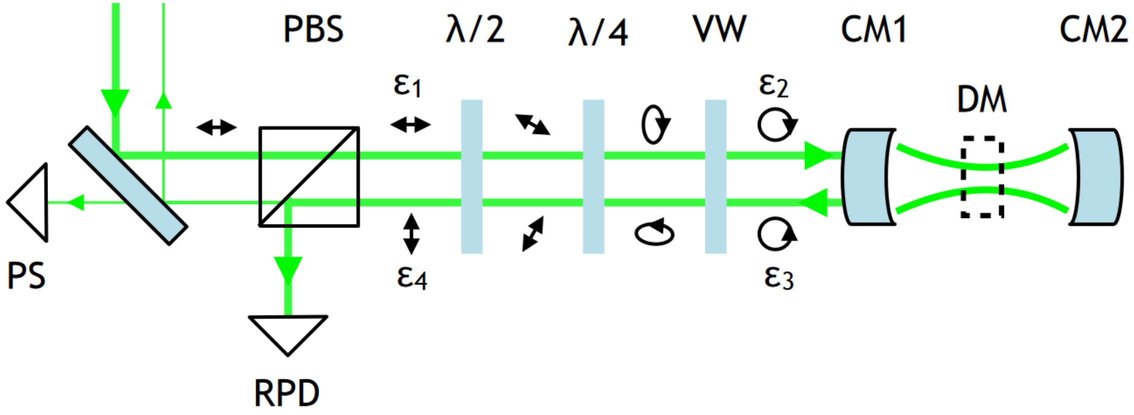
- Typically the polarization is monitored through measurements of the transmitted laser light (after the IP)
- The “transfer function” can be measured on the bench but variations (such as tightening bolts or pulling vacuum) change the function making it unusable for the actual data taking
- Tests done with cavity at JLab showed that large differences in the degree of circular polarization can be obtained when straining the windows

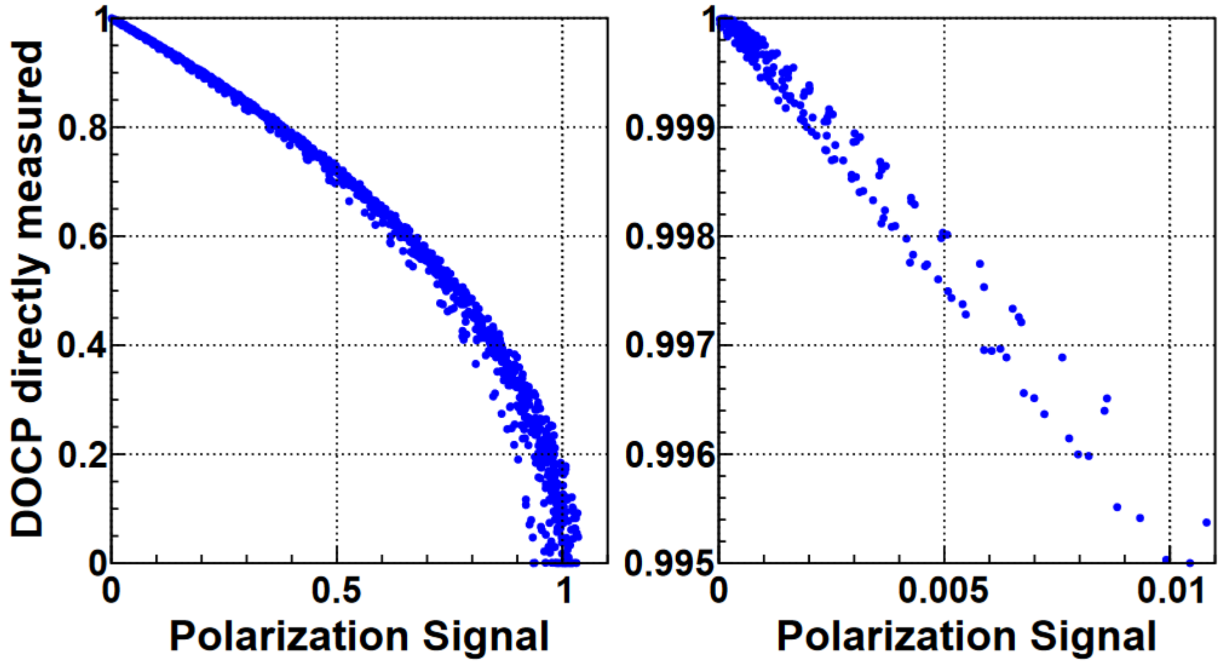


Dealing with window birefringence

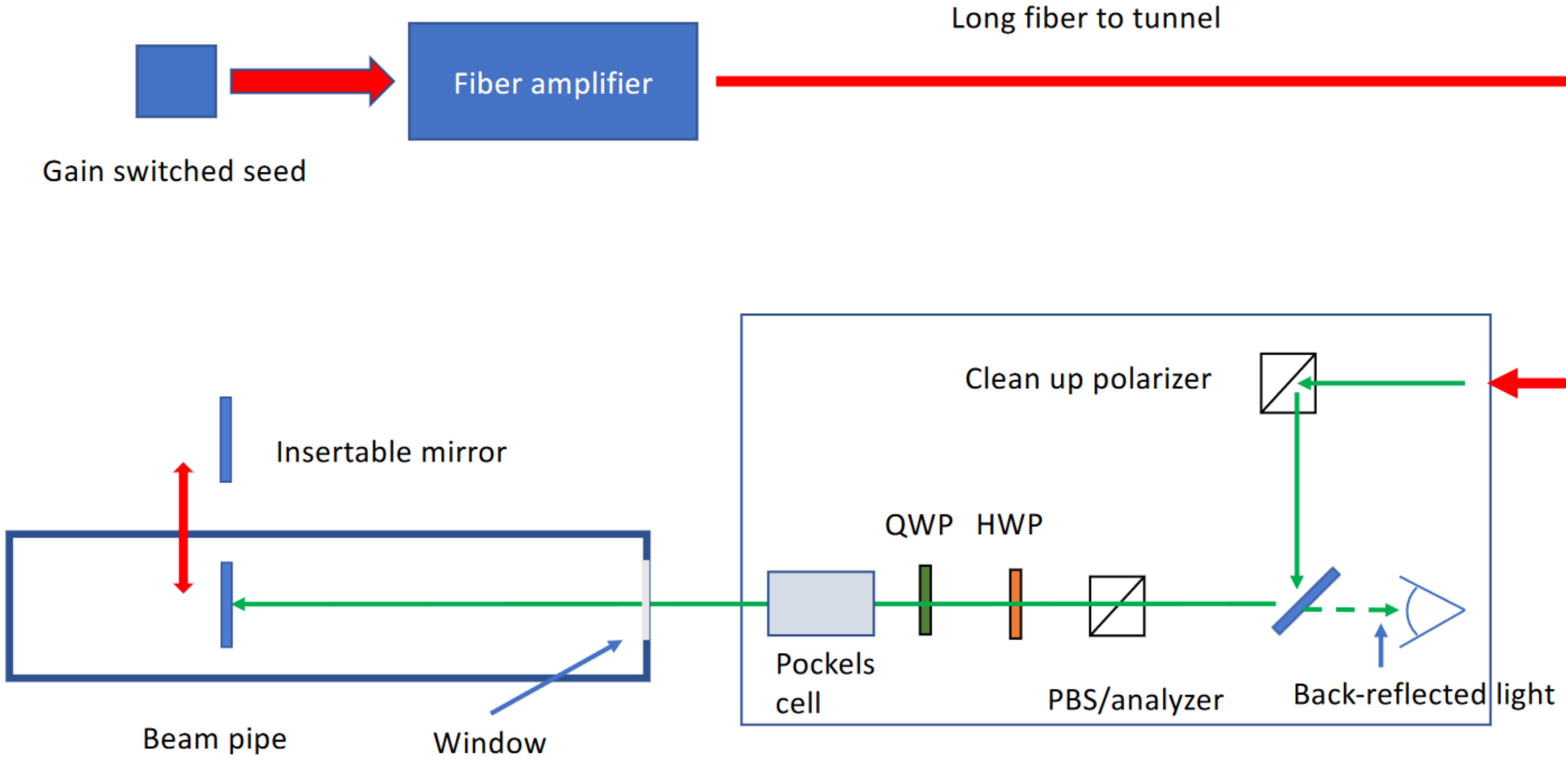
arXiv:1509:06642v2

- In order to obtain circular polarization at the interaction point with the electron beam one can use the information obtained from the back-reflected light
  - In this case it would be off of mirror M1
- Using the optical reversibility theorem one can relate the amount of light reaching "PS" to the degree of circular polarization inside the cavity
  - M. Dalton and D. Jones showed this to be true in a setup at JLab
- By performing detailed scans of the half and quarter wave plates one can maximize the circular light at the IP and monitor it throughout the data taking





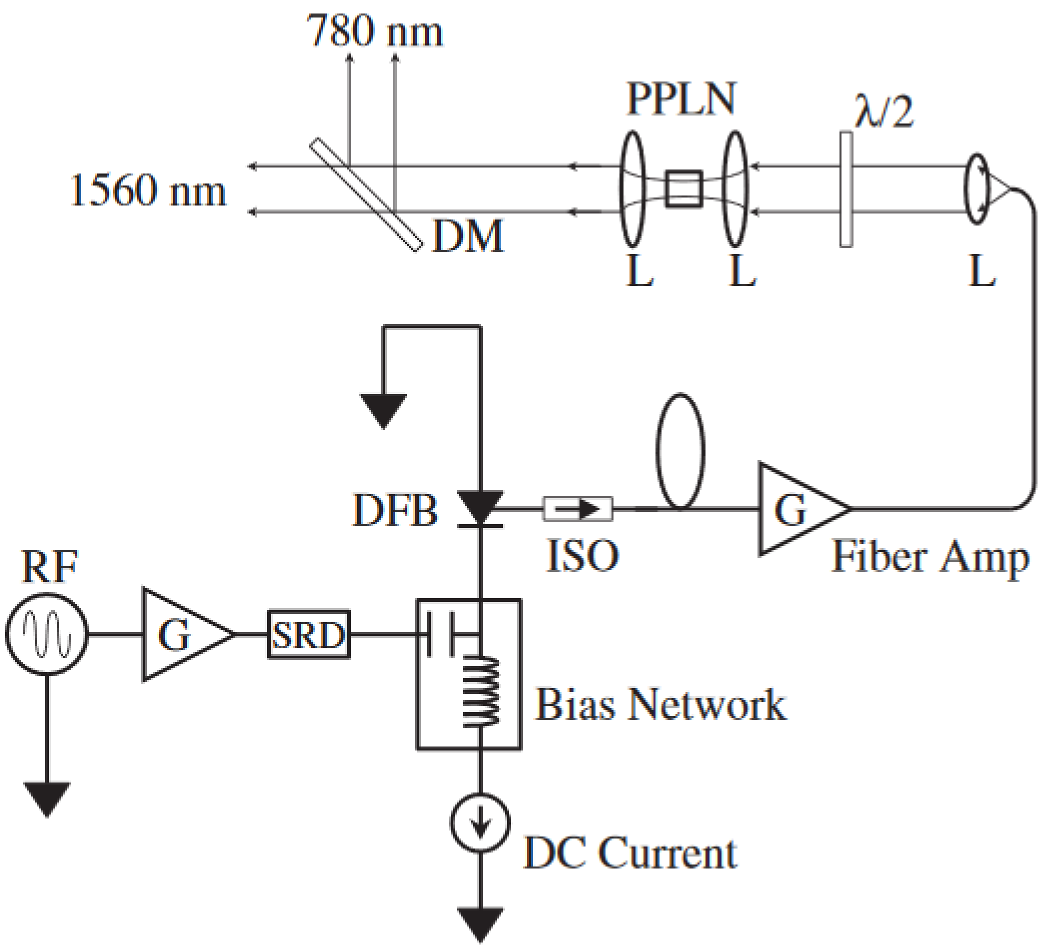
Current design of EIC laser system



- The initial laser system design uses most of the design features highlighted in the previous Compton polarimeter implementations
  - As was before we need the laser system to be away from potential fatal radiation fields inside the tunnel (we plan to evaluate the use of high power laser fiber)
- The vacuum resident insertable mirror will be needed in order to be able to monitor the DOCP at the interaction point

Gain switched seed

- The gain switched seed laser design developed at CEBAF for the injector satisfies all the requirements that we discussed so far
  - The RF lock allows us to synchronize to all or specific electron bunches
  - The pulse longitudinal width will be smaller than the electron bunch (allowing us to potentially measure the longitudinal polarization profile)
  - The PPLN or LBO crystal will allow us to frequency double the 1064nm light to 532
- The system has proven to be very reliable and has been adopted by other facilities (such as the Maintz Microtron)



Phys. Rev. ST Accel. Beams 9, 063501 (2006)
https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.9.063501

Project and Deliverables

Year 1

- Detail design of laser system
- Seed and preamp construction
  - Low power characterization

Year 2

- High power fiber amplifier
- Fiber delivery
- Frequency doubler
- Design vacuum system

Year 3

- Check 100% DOCP laser polarization through vacuum windows
- Remote control stages
- Picomotor controller
- Potential test at JLab
- Publish results

Budget

Item	Cost[$]
Seed: Laser diode	12000
Seed: Pulse driver	20000
Seed: Preamplifier	10000
Seed: Controllers	13000
Seed: Fiber optics	5000
Gain switched seed and preamplifier total	**60000**
Fiber power amplifier	45000
Single-mode fiber (20m)	5000
Frequency doubler	5000
Total	115000

Item	Cost[$]
QWP (2)	1000
HWP	500
Pockels cell	2500
Polarizing cubes (3)	260
Mirrors (10)	700
Remote controlled stages (3)	10700
Picomotor controller (2)	3100
Assorted stands	2000
Total	20760

- The proposed system has two major components
  - The laser itself and fiber transport
  - The optics needed to prepare and characterize the laser polarization
- Labor to be provided by collaborative institutions with SBU taking the lead and JLab and UVa playing a technical supervisory role
  - 0.3 FTE C. Gal; 0.3 FTE CFNS/joint postdoc; 0.5 FTE SBU Master student for the first year

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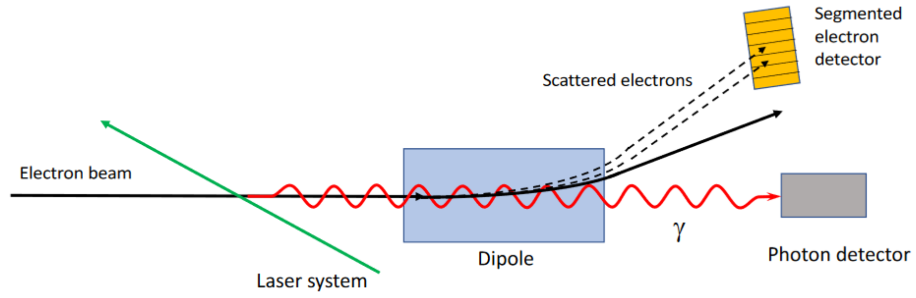
Year 1
65k$

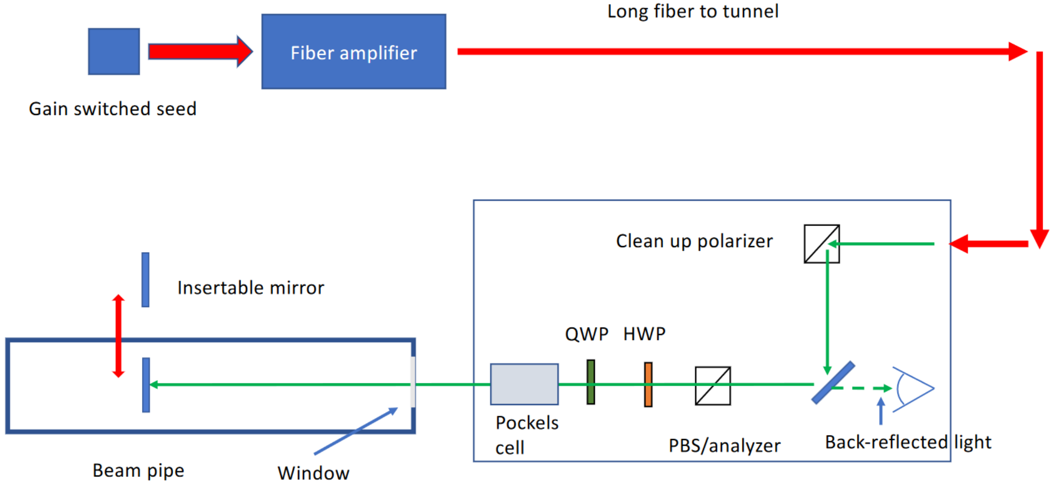
Year 2
57.5k$

Year 3
14k$

Summary and Challenges

- A Compton polarimeter is the ideal system to measure and monitor e-beam polarization
- The proposed system would satisfy all the requirements for the EIC Compton polarimeter and reach ~1% uncertainties
  - The 10W laser power would be sufficient to obtain at least one collision per bunch crossing allowing us to make a fast measurement of each bunch
  - The variable frequency would allow for background measurements and systematic studies
  - The proposed optics elements would allow for the characterization and continuous monitoring of the laser polarization properties
  - The high power fiber transport will need to be tested in order to allow for a robust system





Backup

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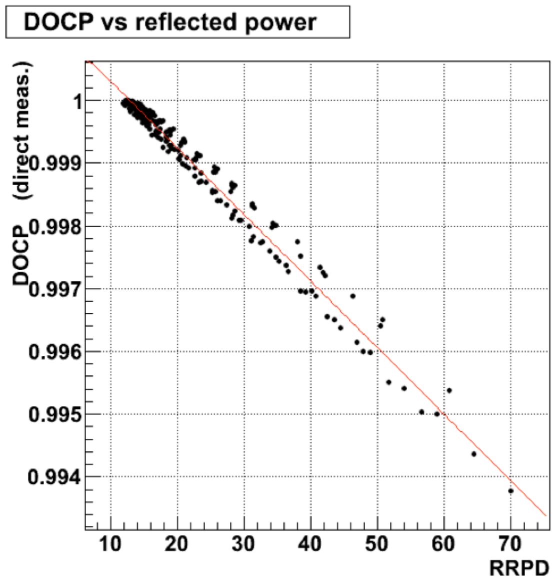
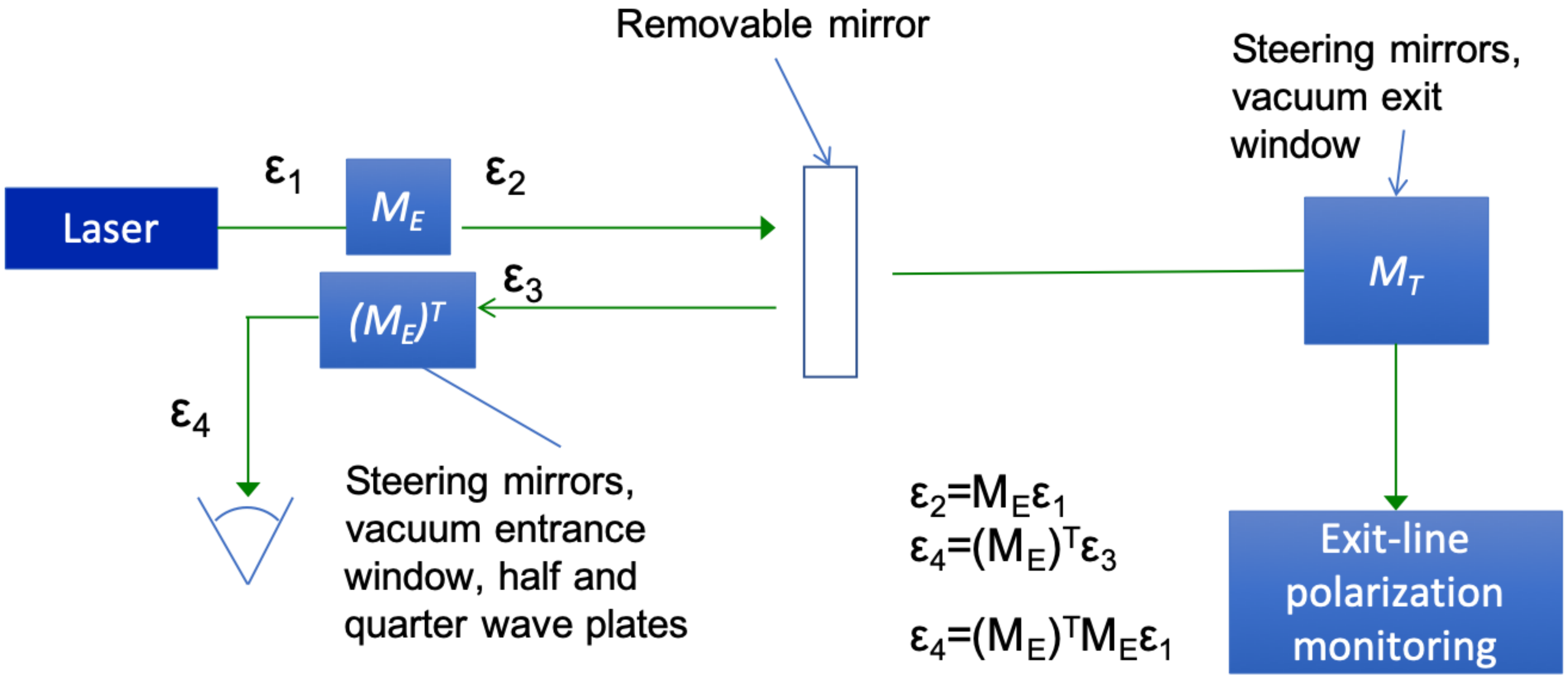
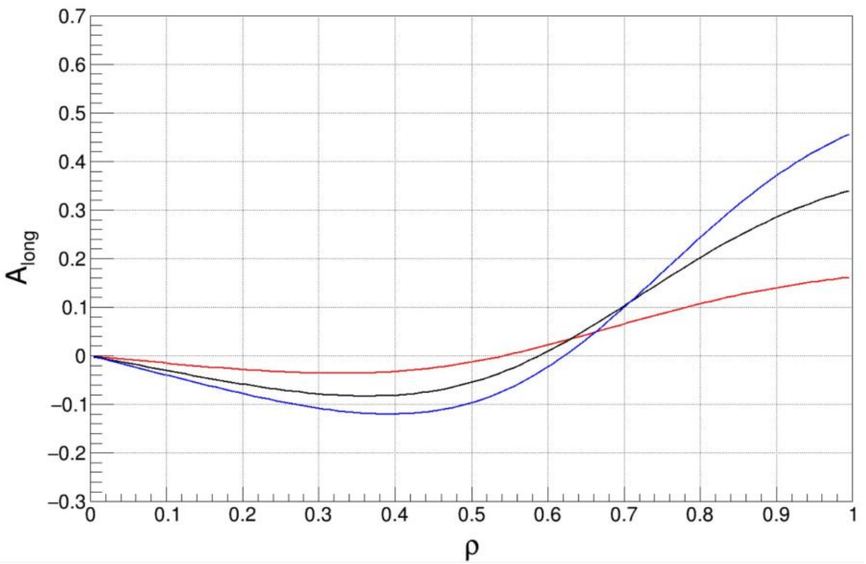




- The polarization setup for the EIC Compton will follow the same logical reasoning as the Jefferson Lab measurements

Longitudinal vs transverse

$$A_{\text{long}} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1-\rho(1+a))\left[1 - \frac{1}{(1-\rho(1-a))^2}\right]$$



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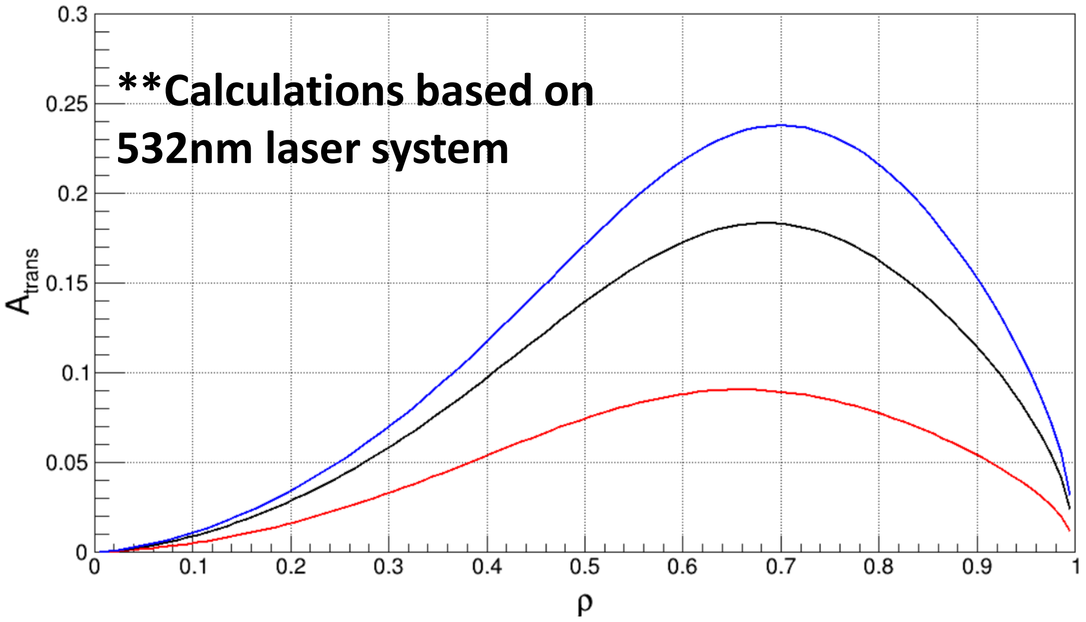

- While both cases have dependence on energy the transverse also has an azimuthal dependence

Longitudinal polarization

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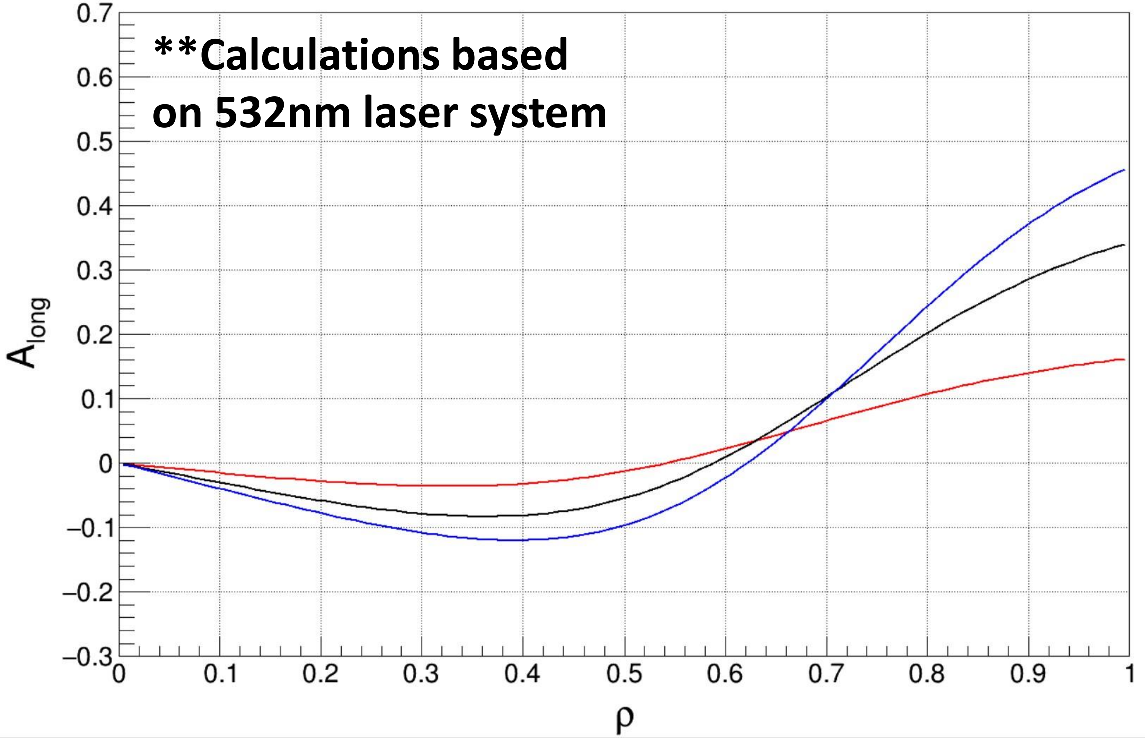
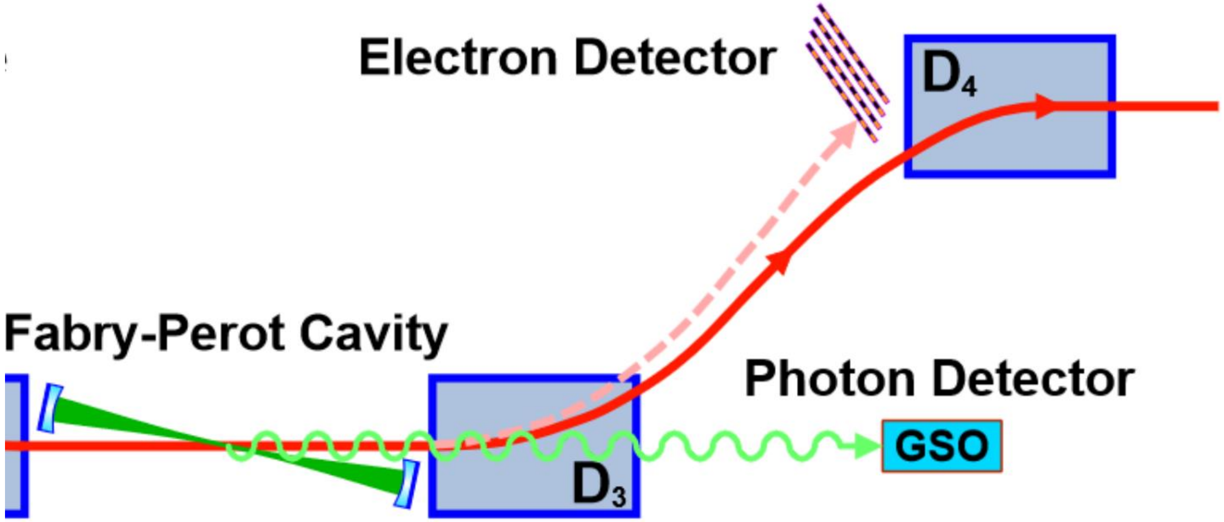


arXiv:1601:00251v2

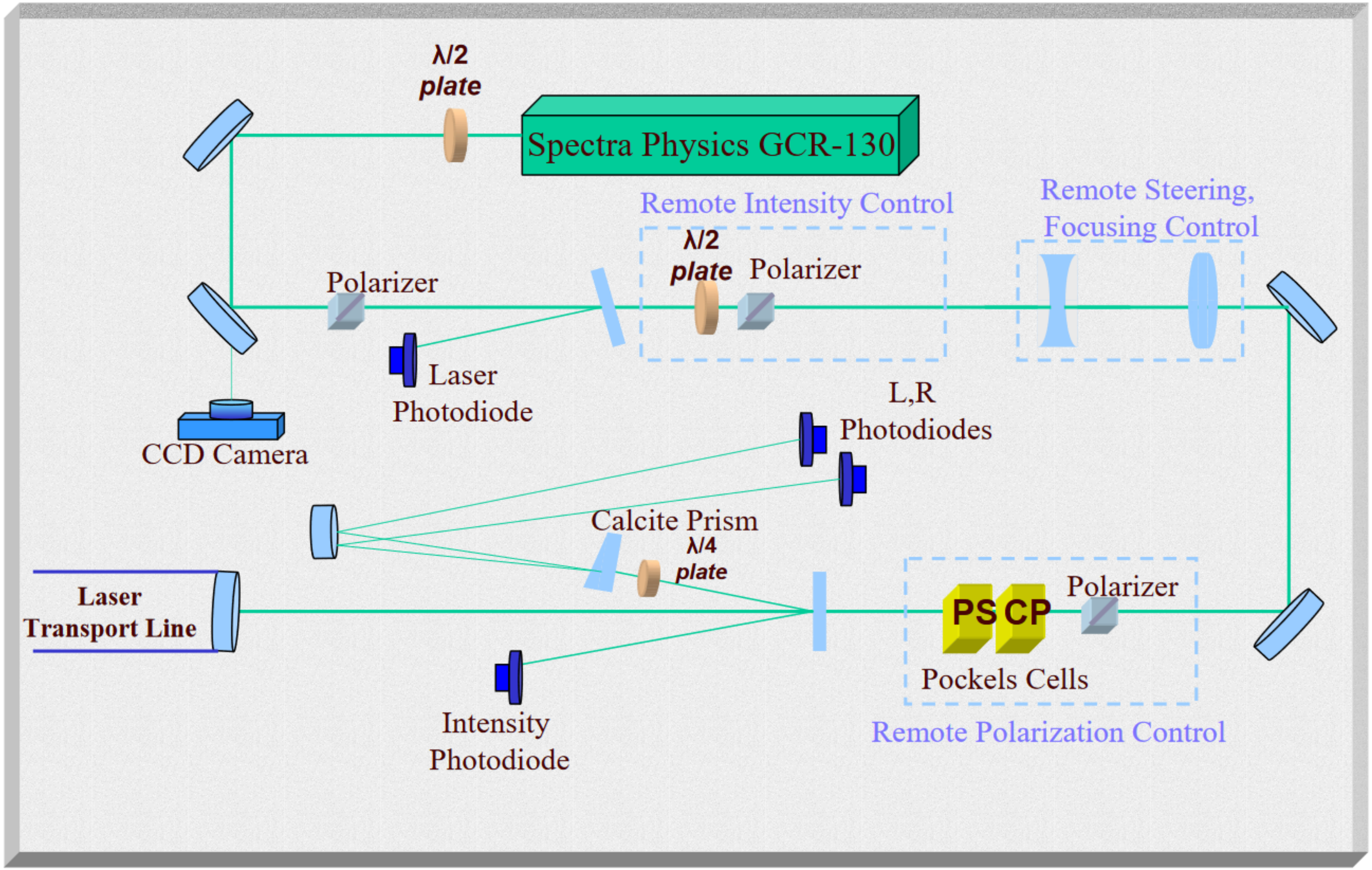


- The energy in the photon detector can measured with calorimetry while the electron is momentum-analyzed by a dipole after the interaction
  - No transverse differences exist for the photon
- Allows for relatively simple analysis of multi-particle crossing

M. Woods: (https://www.jlab.org/polarimetry/talks/woods_sld.pdf)

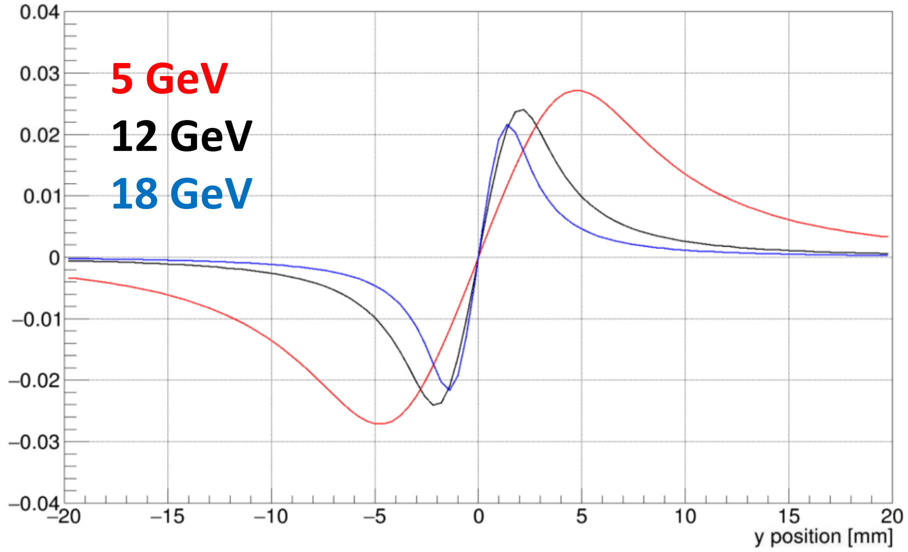
SLD laser setup

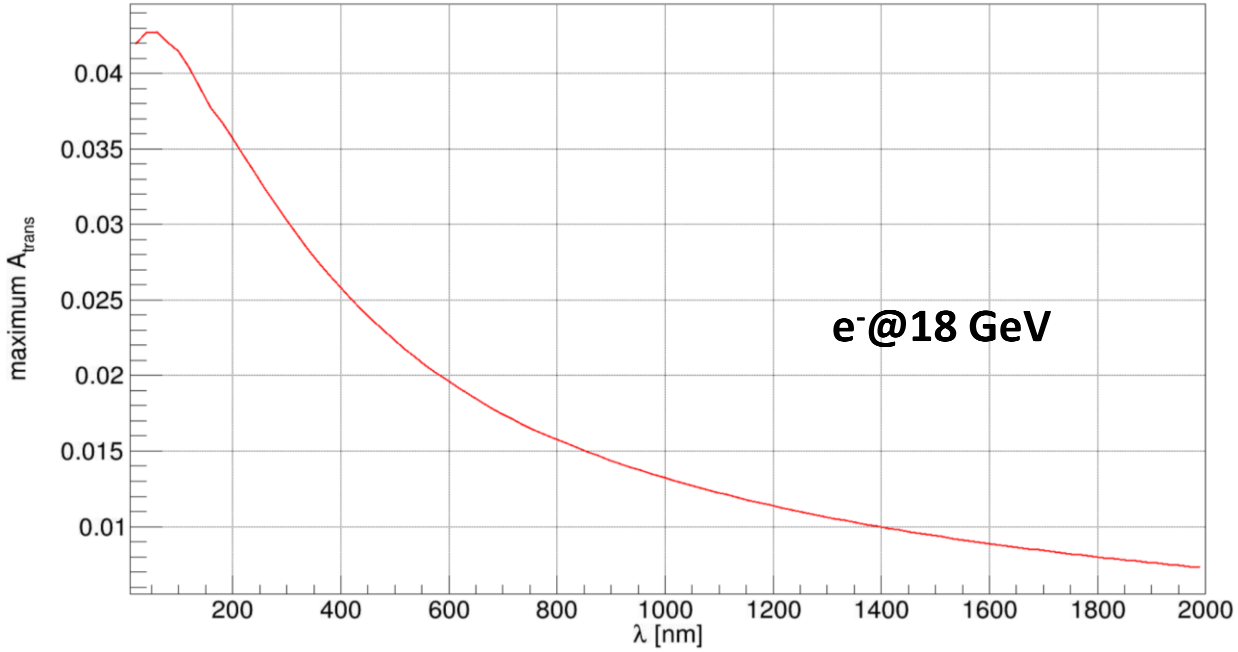
- The laser setup for most Compton polarimeters is fairly standard
- Beyond reaching the needed luminosity the laser needs to be circularly polarized at the IP
  - Pockels cells in combination with quarter or half wave plates allow for an arbitrary laser configuration setup (to compensate for any distortions before the IP)
- Polarization and intensity monitoring is setup to ensure reliable operation



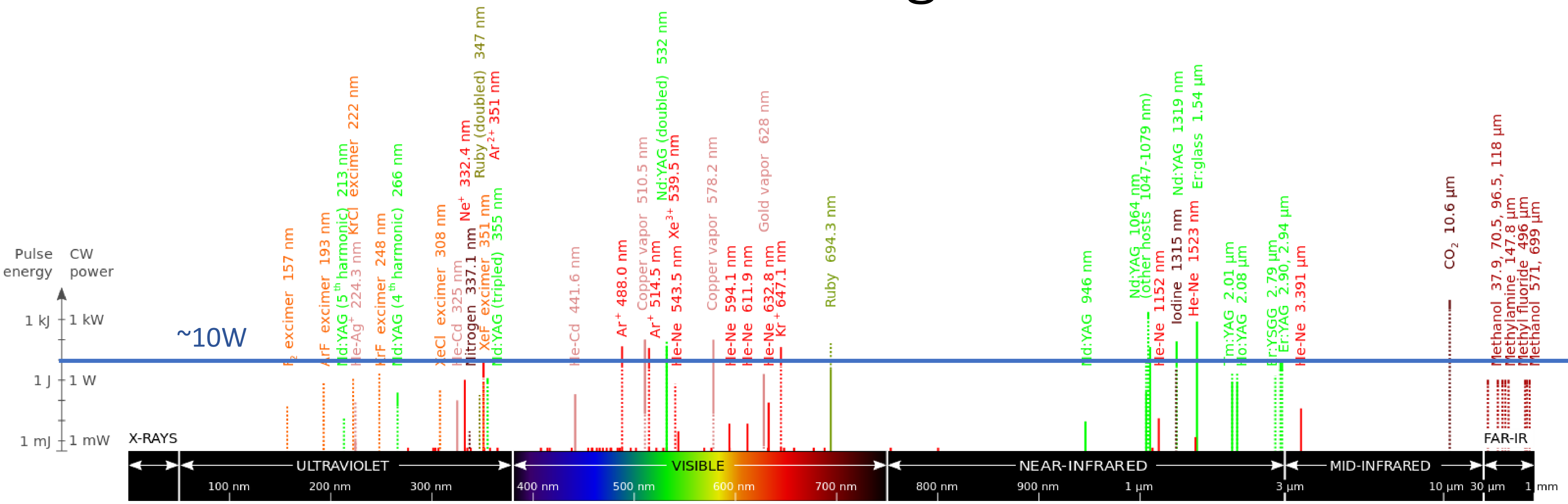
Wavelength dependence for analyzing power

- The maximum analyzing power increases with lower laser wavelength reaching a peak close to 100nm
- Additionally we can see the position of peak gets further spread out allowing for easier detection
- The longitudinal analyzing power shows similar behaviour, just on a different scale





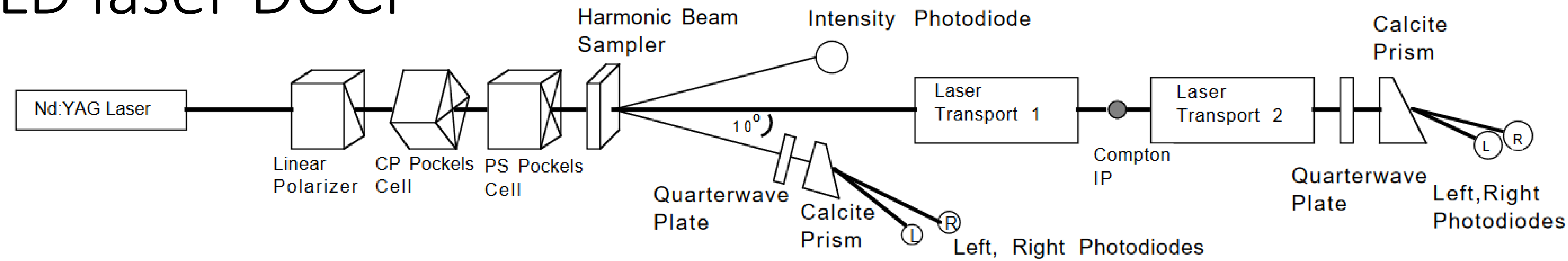
Lasers as a function of wavelength



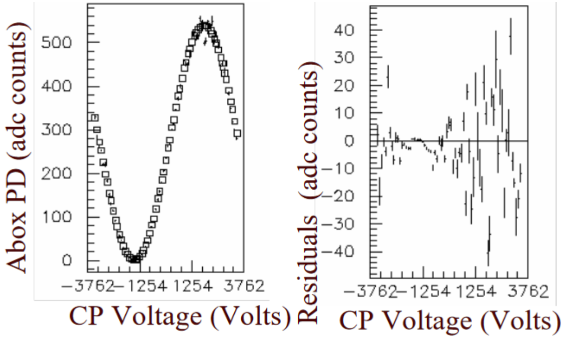
- When looking for a laser we need to take into account ease of setup and reliability
  - There is a good reason most Compton polarimeters used Nd:YAG lasers at their core
  - A low power Nd:YAG laser can be amplified quite readily to larger powers without much custom equipment
- Additionally we need to make sure we can have enough power from the laser to provide sufficient luminosity (few Watts of power will be needed)

SLD laser DOCP

M. Woods arXiv:hep-ex/9611005v1

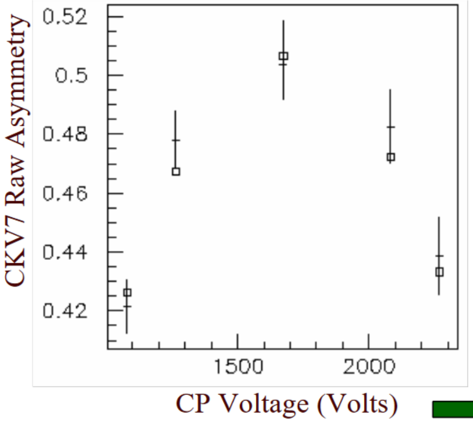


- The SLD laser monitoring setup already has all the needed tools
- Scans performed with the PC during the experiment and data taking allowed for significantly reduced systematics related to the polarization state of the laser



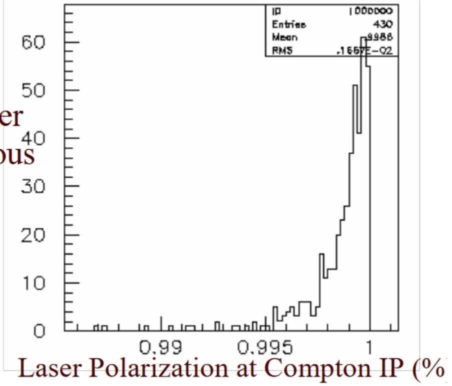
LPSCANS

- done once per hour; readout photodiodes only
- ability to extinguish laser light after Helicity Filter determines polarization purity



ESCANS

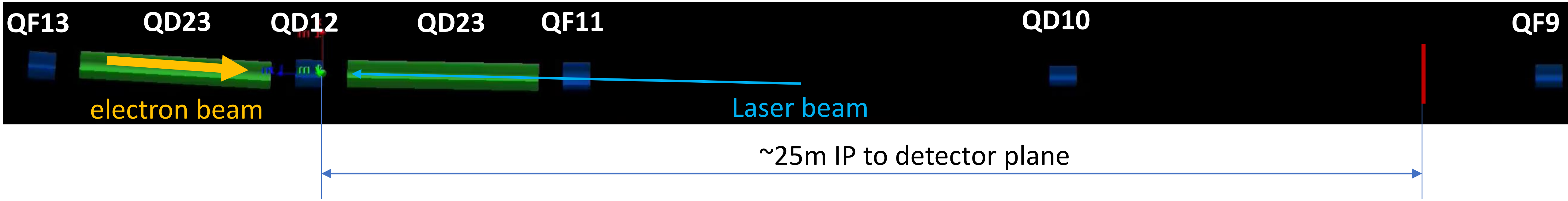
- monitor phase shifts in laser Polarization with continuous Pockels cell scans
- only 1/3 of data is at nominal voltages

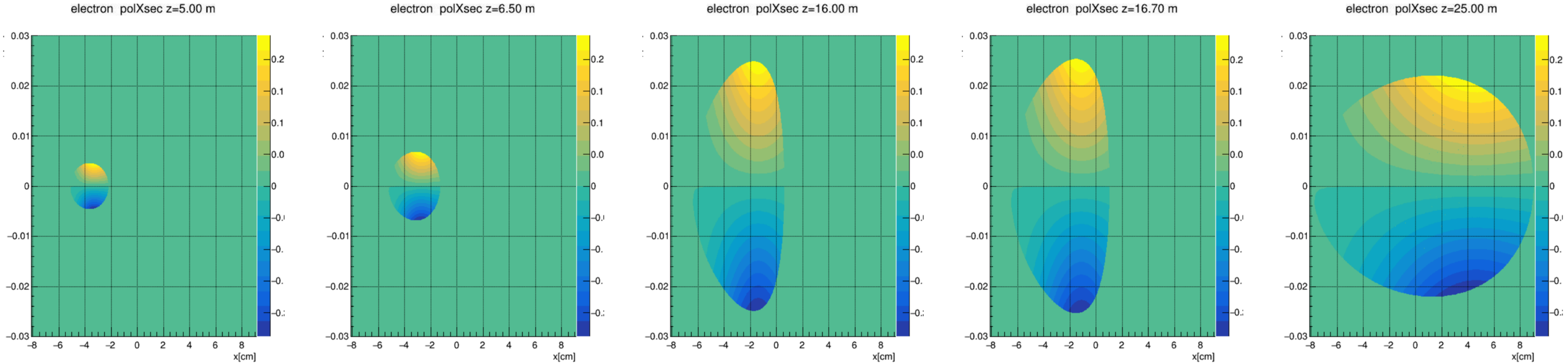


0.1% systematic error

M. Woods, SLAC

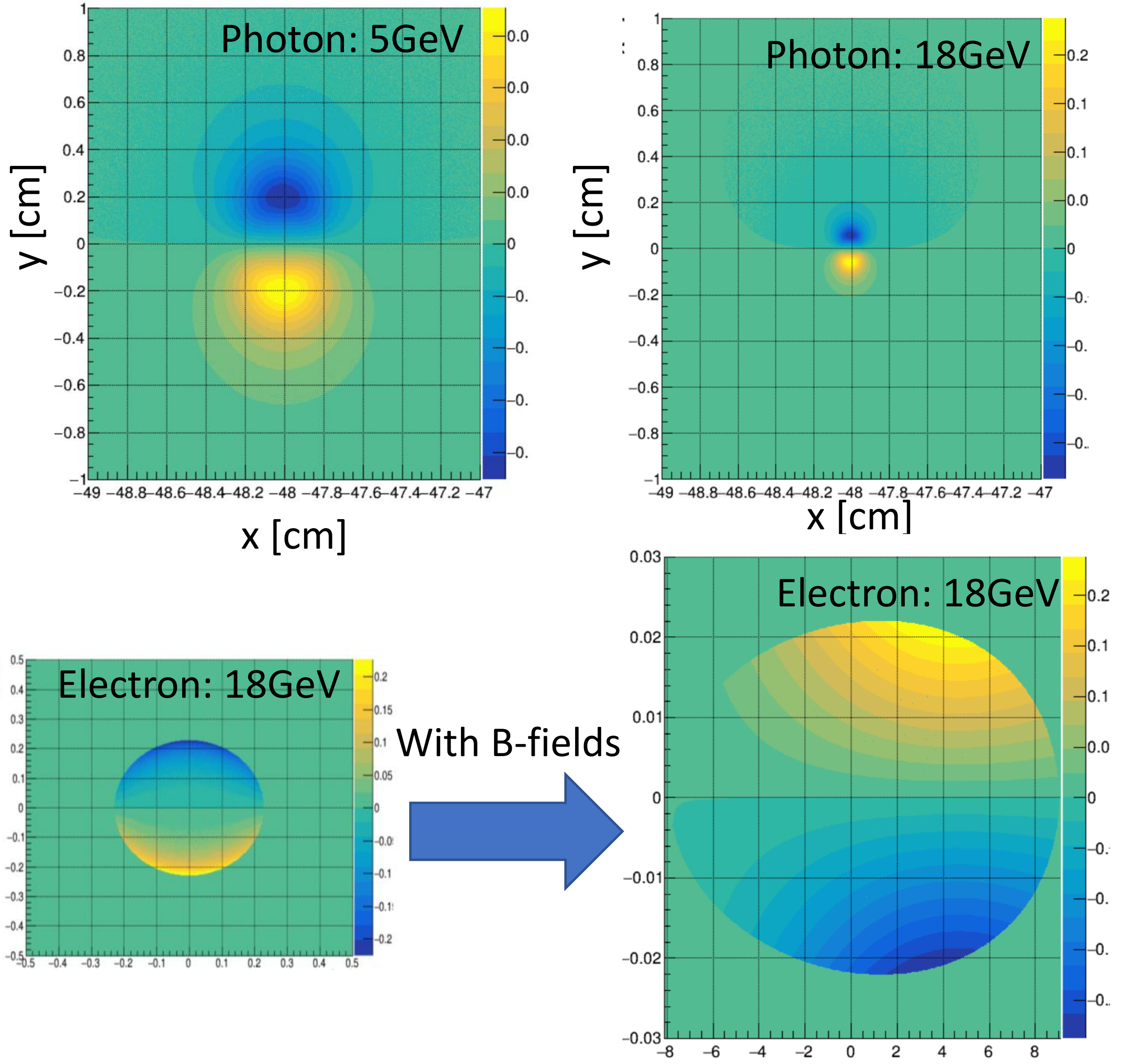
Layout at IP12





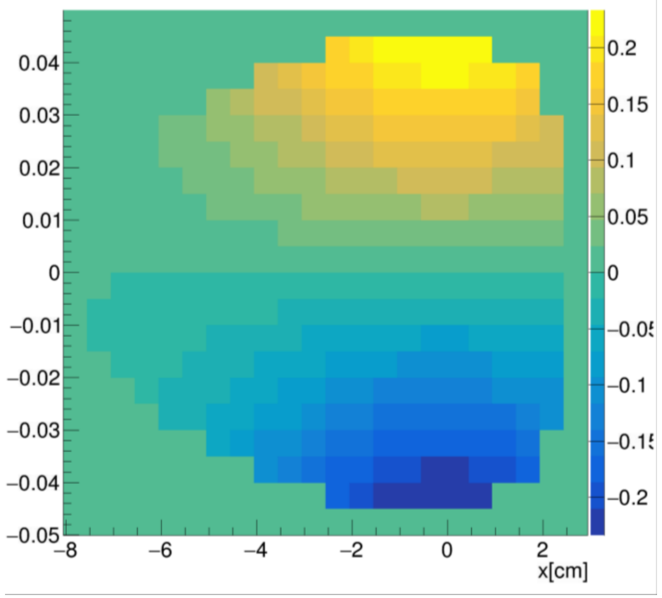
- As the scattered particles pass through the different magnets the electrons are stretched horizontally
- At the detector plane we can clearly see both the spatial and energy dependence

Envelopes at detector plane



- 18 GeV will provide the most stringent requirements for the photon detector due to the small vertical separation between the two peaks of the asymmetry
- The electrons have a extreme almond shape with a ratio between the horizontal and vertical extent of about 320
  - The momentum analyzed electrons show the peak analyzing power at about 30% of the minimum energy as expected
- A preliminary analysis of the vertex smearing show that the transverse extent of the electron beam will have an important effect by almost doubling the vertical axis

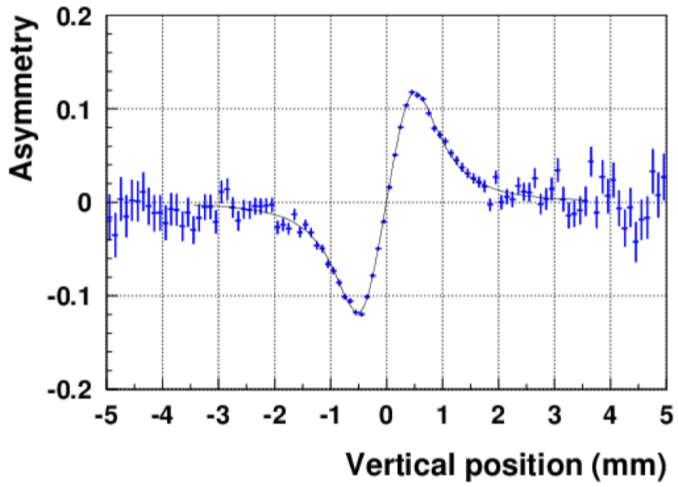
Detector segmentation



Input normalization: 73%

segmentation [um]	Extracted normalization
400	30.53
200	75.71
100	73.74
50	73.43
10	73.01
5	73.00

- By segmenting the simulated signal vertically and assigning an arbitrary normalization one can use the unbinned distribution to extract the normalization
- This rough analysis gives us a feel for what the vertical segmentation of the two detectors will need to be
  - For the photon detector a segmentation of better than 200 micron will be needed
  - The electron detector will require a 50 micron or better segmentation



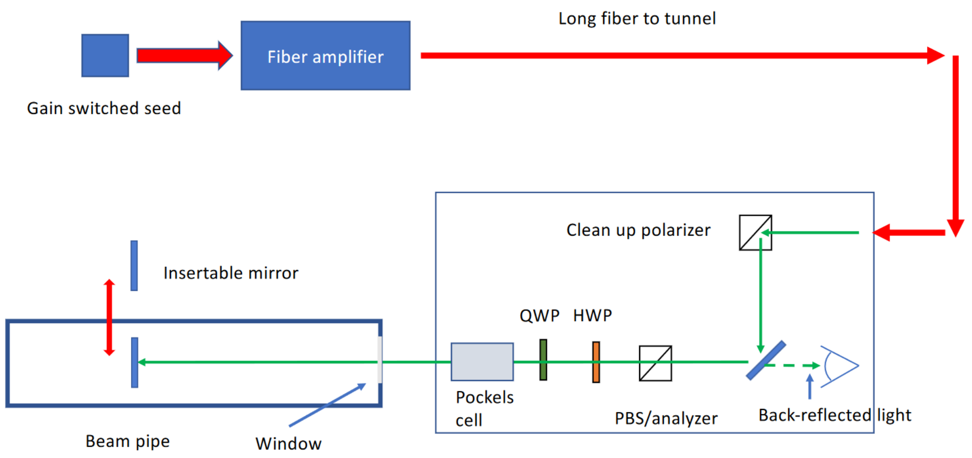
Input normalization: 85%

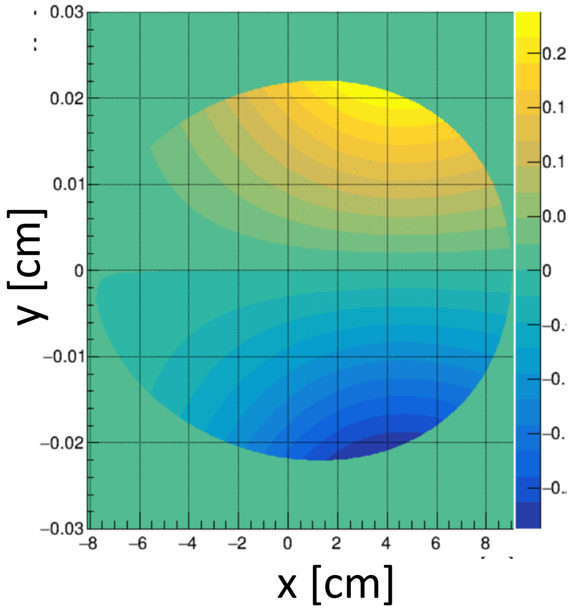
segmentation [um]	Extracted normalization
500	77.7
400	80.4
333.33	82.7
200	84.4
100	85.1
50	85.0

Calculation done by D. Gaskell

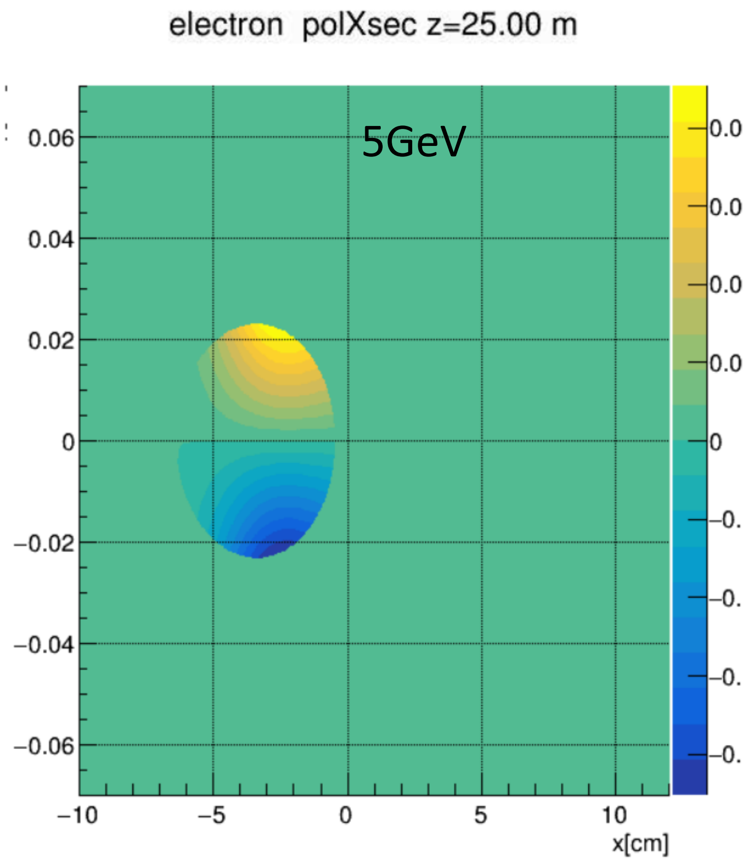
Summary and outlook

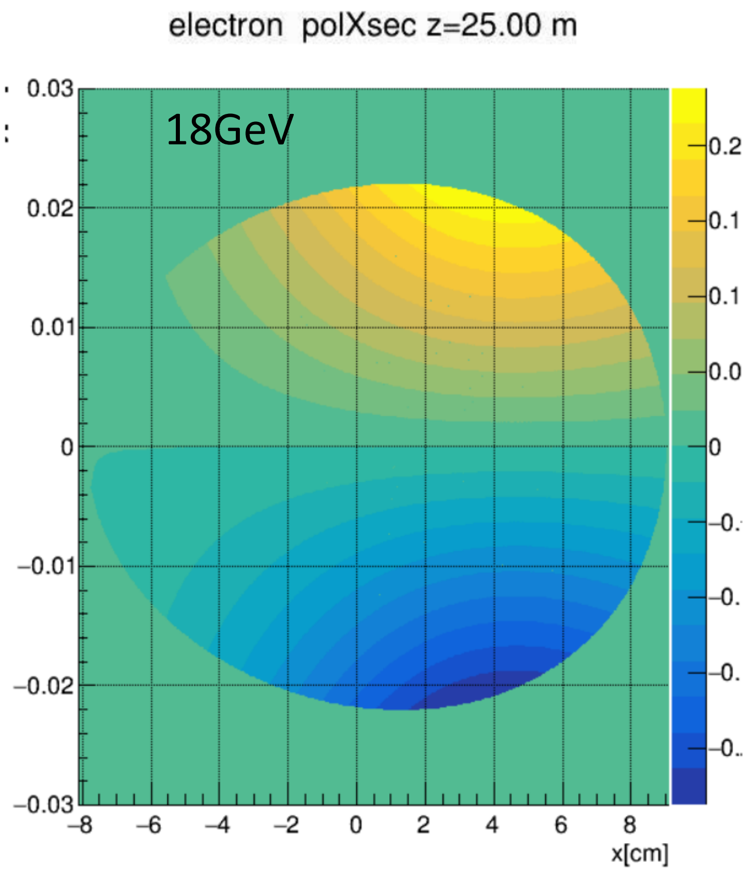
- For the EIC we are trying to incorporate all the lessons that were learned at previous facilities
- A single pass 10 W pulsed laser provides enough luminosity to be able to measure bunch by bunch polarizations on the level of minutes with 1% statistical precision
  - At 2min lifetime for 18GeV we can still reach the 1% goal if we consider the luminosity weighted polarization
- Careful analysis needs to be done for the IR location
  - A longitudinal polarimeter seems to more likely there
  - This would provide a significant cross check on the IP12 Transverse polarimeter and we can combine the results (as HERA did)





5 vs 18 GeV at e det plane





HERA (T) systematics

Source of Uncertainty	$\delta P/P$ (%)	Class	Comment
Description of Photon Generation, IP and Photon Beam Line			
HERA Beam Optics	0.5	IIId	7 different optics
Lepton Beam Line	0.5	IId	Mainly beam position in quadrupole
Lepton Beam Horizontal Emittance	0.1	IIId	
Laser Beam Line	0.2	IId	
Lepton Laser Beam Crossing	0.1	IIId	
Tilt of Photon Beam Ellipse	0.1	IIId	Mostly $\approx 2° - 4°$
Photon Pileup: Multi Photon Interaction	0.1	I	
Calorimeter Response			
Average Response	0.6	IIu	
- $\eta(y)$ and $E(y)$	(0.2)		Up and Down channels
- Difference converted to non-converted Photons	(0.2)		
- Linearity of Calorimeter Response	(0.2)		
- Effective $\eta(y)$ Calibration	(0.5)		Eff. Silicon strip pitch
- Horizontal and LR-channels Response	(0.1)		
Energy Resolution	0.7	IIu	
- Total Energy Resolution	(0.4)		Fits to Compton edges
- Central spatial Description	(0.2)		
- Difference converted to non-converted Photons	(0.1)		
- Resolution Correlations	(0.5)		Channels sharing the same shower
Signal Modelling	0.3	IIu	
- Digitisation	(0.1)		
- Cross Talk and Non-linearity	(0.3)		
Horizontal Beam Position	0.2	IId	

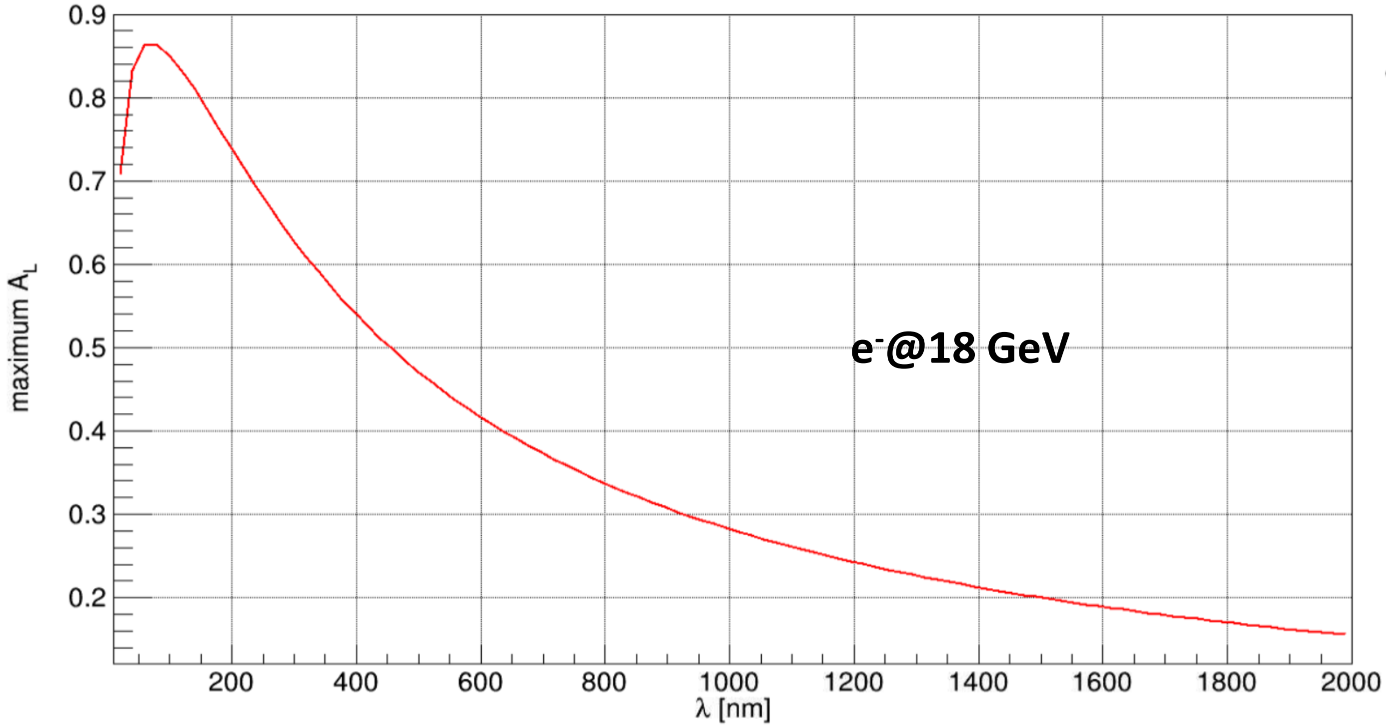
Source of Uncertainty	$\delta P/P$ (%)	Class	Comment
Data Calibration			
Absolute Gain	0.3	I	Beam energy changing with time
Gain Difference	0.3	I	Channels Up vs Down
Vertical Table Centring	0.1	I	
Background Subtraction	0.1	I	
Fitting Procedure			
Method Uncertainty	0.5	I	Covering complete phase space
Quality of Maps	0.2	I	MC Statistics, smoothing and interpolation
Impact of Starting Values	0.2	I	
IP Distance Reconstruction	0.5	I	Random jumps in data
Pedestal Shift Impact	0.5	IId	Global impact estimated from data
Laser Light Properties			
Linear Laser Light Polarisation	0.2	IId	
Trigger Threshold			
Bias at low Energies	0.2	IId	
Machine Performance			
Emittance Reconstruction	0.9	IId	Comparison with expected emittances

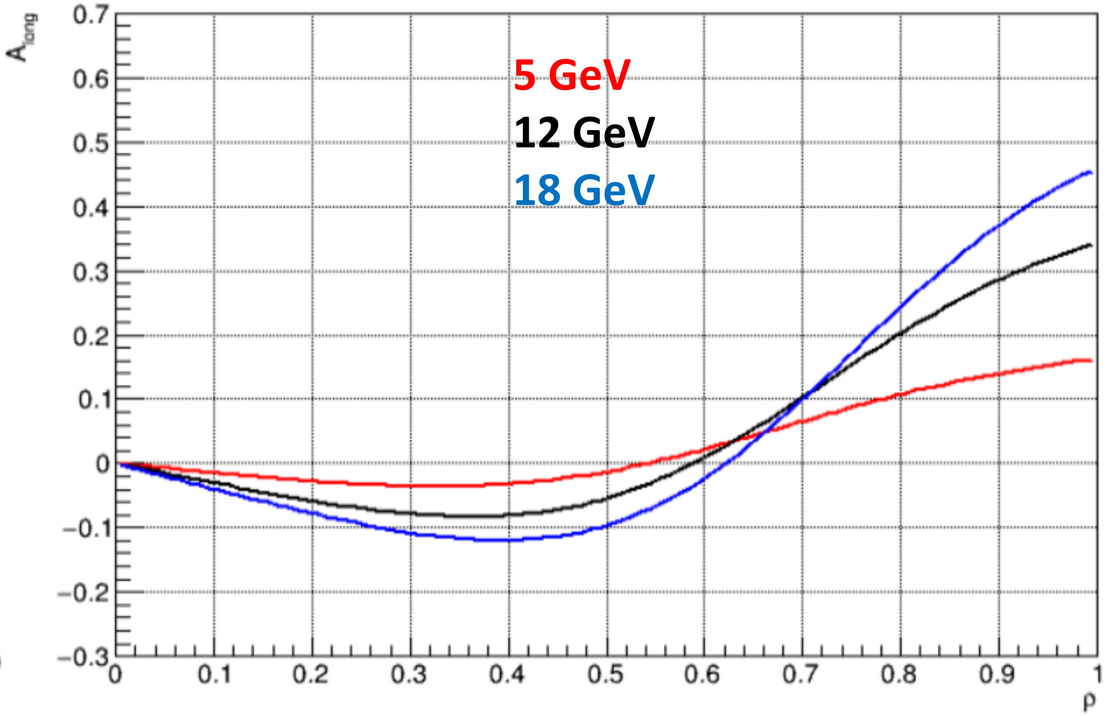
M. Woods: (https://www.jlab.org/polarimetry/talks/woods_sld.pdf)

SLD

Systematic	1992	1993	1994/95	1996	1997/98
Laser Polarization	2.0%	1.0%	0.2%	0.1%	0.1%
Detector Linearity	1.5%	0.6%	0.5%	0.2%	0.2%
Analyzing Power	1.0%	0.6%	0.3%	0.4%	0.4%
Laser Pickup	0.4%	0.2%	0.2%	0.2%	0.2%
Lum-wting Correction	0.2%	1.1%	0.17%	0.16%	0.15%
TOTAL	**2.7%**	**1.7%**	**0.67%**	**0.52%**	**0.52%**

Wavelength dependence for longitudinal analyzing power





JLab Compton polarimetry

Source	Uncertainty	ΔP/P%
Laser Polarization	**0.18%**	**0.18**
helicity correl. beam	5 nm, 3 nrad	< 0.07
Plane to Plane	secondaries	0.00
magnetic field	0.0011 T	0.13
beam energy	1 MeV	0.08
detector z position	1 mm	0.03
trigger multiplicity	1-3 plane	0.19
trigger clustering	1-8 strips	0.01
detector tilt (x, y and z)	1 degree	0.06
detector efficiency	0.0 - 1.0	0.1
detector noise	up to 20% of rate	0.1
fringe field	100%	0.05
radiative corrections	20%	0.05
DAQ efficiency correction	40%	0.3
DAQ efficiency pt.-to-pt.		0.3
Beam vert. pos. variation	0.5 mrad	0.2
spin precession in chicane	20 mrad	< 0.03
Electron Detector Total		**0.56**
Grand Total		**0.59**

Time for 1% measurements

Assume 1 photon/electron per crossing		Average asymmetry						
Configuration	Beam energy [GeV]	Unpol Xsec[barn]	A	A^2	L	1/t(1%)	t[s]	t[min]
laser:532nm, photon	18	0.432	0.072	5.18E-03	1.81E+05	2.93E-02	34	0.57
laser:532nm, electron	18	0.432	0.075	5.63E-03	1.81E+05	3.18E-02	31	0.52
laser:1064nm, photon	18	0.333	0.046	2.12E-03	2.35E+05	1.20E-02	84	1.39
laser:1064nm, electron	18	0.333	0.046	2.12E-03	2.35E+05	1.20E-02	84	1.39
laser:532nm, photon	5	0.569	0.031	9.61E-04	1.37E+05	5.43E-03	184	3.07
laser:532nm, electron	5	0.569	0.029	8.41E-04	1.37E+05	4.75E-03	210	3.51
laser:1064nm, photon	5	0.339	0.017	2.89E-04	2.31E+05	1.63E-03	613	10.21
laser:1064nm, electron	5	0.339	0.015	2.25E-04	2.31E+05	1.27E-03	787	13.11
laser:532nm, photon	12	0.482	0.057	3.25E-03	1.62E+05	1.84E-02	54	0.91
laser:532nm, electron	12	0.482	0.056	3.14E-03	1.62E+05	1.77E-02	56	0.94
laser:1064nm, photon	12	0.327	0.034	1.12E-03	2.39E+05	6.34E-03	158	2.63
laser:1064nm, electron	12	0.327	0.033	1.10E-03	2.39E+05	6.23E-03	161	2.68

Compton polarimeters through history

Polarimeter	Energy	Total Sys. Uncertainty	Type of laser	Measurement type
CERN LEP (T)	46 GeV	5%	~10s Hz pulsed Nd:YAG (532nm): 50 -100 W	Multi-photon
HERA (T)	27 GeV	1.9%	CW 10W (514.5nm) Argon	Single-photon
HERA (L)	27 GeV	1.6%	100Hz pulsed 10W Nd:YAG (532nm)	Single/Multi-photon
HERA (L)	27 GeV	1%	CW cavity 3 kW,	Single-photon
SLD at SLAC (L)	45.6 GeV	0.5%	17 Hz pulsed ?? W Nd:YAG (532nm)	Multi-photon
JLab Hall A (L)	1-6 GeV	1-3%	CW cavity 3.7 kW Nd:YAG (532nm)	Single/Multi-photon
JLab Hall C (L)	1.1 GeV	0.6%	CW cavity 1.7 kW Nd:YAG (532nm)	Single/Multi-photon

- Beyond LEP there were quite a few transverse polarimeters around the world that were used for beam diagnostics (an absolute polarization was not in the plan)
- Longitudinal polarimeters are easier to calibration due to the Compton edge and the 0-crossing, making the data easier to analyze
- Pulsed lasers generally tend to give more interactions per crossing so a multi-photon (or integrating) method was employed